NACA

RESEARCH MEMORANDUM

STUDY OF THE PHYSICAL PROPERTIES OF PETROLATUM-STABILIZED MAGNESIUM-HYDROCARBON SLURRY FUELS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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Page 5, paragraph 4, line 8: The composition of the medium should be given as 28 percent petrolatum E and 72 percent JP-4 by weight.

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SUMMARY

Several pertinent physical characteristics of magnesium - JP-4 slurry fuels made with magnesium powder of 18-micron average particle diameter and stabilized with five different petrolatums have been studied. The results indicate that slurries of this type, which offer promise as aircraft fuels, can be prepared easily and can be remixed to their original condition after storage. Successive batches have closely similar properties. The apparent viscosity of these slurries is greatly dependent on the temperature.

While no quantitative correlation was found between the characteristics of the slurry and those of the petrolatum, and no one petrolatum gave slurries which were best in all respects, one of the stiffer, higher-melting, more viscous petrolatums of the five tested was judged to be superior to the other four.

The apparent viscosity of these slurries decreased rapidly with increasing rate of shear. With any one petrolatum, the apparent viscosities at low and at infinite rates of shear of slurries containing 50 percent magnesium increased exponentially as the petrolatum concentration was increased from 14 to 30 percent, while the extent of settling and the ease of remixing decreased. Similar effects were obtained by varying the magnesium concentration from 40 to 65 percent. The viscosity at an infinite rate of shear was found to increase as the viscosity at a low rate of shear increased, while the ease of remixing and the extent of settling after a given interval decreased. When slurries prepared with the same petrolatum were compared at the same apparent viscosity at a low rate of shear, the other measured properties were largely independent of whether this viscosity was controlled by the petrolatum concentration or by the magnesium concentration.

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INTRODUCTION

An analytical evaluation of metal-hydrocarbon slurries at the NACA Lewis laboratory has indicated that magnesium slurry fuels offer a higher thrust level and wider combustion limits in ram-jet engines and afterburners than do the conventional jet-engine hydrocarbon fuels (refs. 1 to 3). Combustion tests carried out in simulated burners have confirmed the analysis (refs. 3 and 4). It has been found desirable to introduce the magnesium into the burner as a suspension in hydrocarbon in order to permit control of the amount of thrust by varying the rate of fuel flow, and to permit the use of storage and fuel systems which are not radically different from those used for conventional jet aircraft fuel.

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The effective utilization of slurry fuels requires that the magnesium remain uniformly suspended in the hydrocarbon as long as possible. Stabilizing additives have been proposed as a means of retarding the settling of the powder, but the other properties of the slurry are greatly affected by the nature of the stabilizer. The properties of slurries stabilized with aluminum octoate, which gels the hydrocarbon, have been reported in reference 5. While slurries stabilized in this manner have many desirable qualities, it was found difficult to prepare duplicate batches with similar properties (as suggested in ref. 4). In addition, the gel structure often breaks down in a short time, and the magnesium settles in a dense, hard cake. When this happens, the slurry cannot be remixed to its original condition.

It was therefore decided to investigate the use of petrolatum to stabilize slurries of magnesium powder in MIL-F-5624A, grade JP-4 fuel. Petrolatum is a viscous mixture of hydrocarbons which has approximately the same heat of combustion as JP-4. Petrolatum-stabilized magnesium slurries (containing a small percentage of surface-active material) prepared in conjunction with this investigation have been burned in a 2-inch-diameter open-ducted combustor. The results were found to be comparable with those obtained with slurries stabilized with aluminum octoate (ref. 6).

The objective of this investigation was to evaluate the effects of (1) composition and (2) the method of preparation on the physical properties of JP-4 slurries of 18-micron magnesium powder stabilized with petrolatum. The composition variables considered were (1) the concentration of each of five petrolatums (with different physical properties) in slurries containing 50 percent magnesium, and (2) the concentration of magnesium in slurries in which the composition of the JP-4 - petrolatum medium was held constant. The latter variable is of interest because reference 2 indicates that the potentially obtainable thrust increases progressively with increasing magnesium concentration in the slurry. Mixtures of each of two petrolatums with various proportions of JP-4 were also examined for comparison with the slurries made with these petrolatums.

The physical characteristics measured were the viscosity at low and high rates of shear, comparative extent of settling, and comparative ease of remixing after settling. The data obtained were used to evaluate the suitability of each of the five petrolatums as a slurry stabilizer, and to determine the effect of magnesium concentration on the viscosity, extent of settling, and redispersibility of slurries.

CRITERIA FOR EVALUATING PHYSICAL PROPERTIES OF SLURRY FUELS

The slurries which were prepared in this investigation were evaluated on the basis of the following physical characteristics: Brookfield apparent viscosity, residual viscosity, sedimentation ratio, and redispersibility. The method of measurement of these characteristics is described in the EXPERIMENTAL section.

The Brookfield apparent viscosity is a measure of the viscosity of the slurry at a very low rate of shear and should therefore not only indicate how the slurry will flow in ordinary handling operations, but should also be related to the rate of settling of the magnesium particles. It is therefore desirable for the slurry to possess the lowest Brookfield apparent viscosity consistent with acceptable settling characteristics.

It is believed that the residual viscosity (apparent viscosity at high shear rates measured on the Severs Extrusion Rheometer and extrapolated to viscosity at an infinite rate of shear) approximates the viscosity of the slurry as it is forced through the fuel system of the aircraft. A low residual viscosity would therefore be desirable. The extrapolation to an infinite rate of shear was chosen arbitrarily because the rate of shear in the fuel system cannot be closely approximated, although it is judged to be very high.

The sedimentation ratio, which is used as a measure of the extent of settling of the magnesium, is the ratio of the concentration of magnesium in the original slurry to the concentration in the settled portion of the slurry. This ratio is used instead of the settling ratio used in reference 5 in order to permit a more valid comparison of the settling characteristics when the magnesium concentration is a variable. A high sedimentation ratio, approaching 1.00 as a limit, is desirable, since it is indicative of only slight settling. Although this determination is purely empirical, and the results are therefore suitable only for comparing one slurry with another, it is judged that a valid estimate can be drawn as to the comparative settling characteristics of the different slurries in drums or tanks. Such information is of interest because it is desirable that slurry fuels be stable for a prolonged period.

The percentage redispersible is in effect a comparative measure of the energy required to remix the slurry after the magnesium has settled. It is the proportion of the settled portion of the slurry which is redispersed by shaking in a manner which is described in the next section. A high percentage redispersible is desirable because it indicates that the slurry can be remixed easily. The shaking procedure which was used for making this measurement was adopted because none of the few reported methods (refs. 7 and 8) of measuring the redispersibility of solids settled from suspension was considered applicable for the present study. The methods which have been reported deal with paint pigments and involve compression of the cake between flat plates or penetration of the settled cake with a rod, a ball, or a cone. It is believed that the shaking procedure reported herein is a more suitable method, since it is more analogous to the mixing procedures which might be used to restore a drum of settled slurry to a uniform suspension. This determination, like the sedimentation ratio, is purely empirical, and the results are suitable only for comparing slurries with one another.

EXPERIMENTAL

Materials

<u>Magnesium</u>. - The magnesium powder used was a commercial product consisting of spherical particles prepared by the atomization of 99-plus-percent-pure magnesium in a helium atmosphere. Analysis of samples of this powder showed that it consisted of over 95 percent free magnesium, the balance presumably being magnesium oxide and the original impurities. The average particle diameter was 18 microns as determined by the air permeability method with the Fisher Sub Sieve Sizer. This was the finest magnesium powder available in adequate experimental quantity at the time of this investigation. The particle size distribution, determined by the air elutriation method with the Roller particle size analyzer, was

Particle size range, microns	Percent by weight
Below 8.5	17.2
8.5 to 17	23.9
17 to 26	15.2
26 to 40	25.2
Over 40	18.5

The following screening analysis of this material was obtained:

Retained on 100 mesh (Tyler screen), percent	trace
Retained on 150 mesh (Tyler screen), percent	trace
Retained on 200 mesh (Tyler screen), percent	0.3
Retained on 250 mesh (Tyler screen), percent	2.1
Retained on 270 mesh (Tyler screen), percent	10.0
Retained on 325 mesh (Tyler screen), percent	13.7
Passed through 325 mesh (Tyler screen), percent	72.0
Loss, percent	1.9

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Liquid hydrocarbons. - With the exception of five samples which were prepared with o-xylene, JP-4 fuel was used throughout the investigation. The properties of the JP-4 and o-xylene are listed in table I.

Petrolatums. - The five petrolatums which were evaluated were chosen so as to represent a range of physical properties found in commercially available petrolatums. They were labelled A, B, C, D, and E in order of their A.S.T.M. melting points. The physical properties of each petrolatum, as reported by the suppliers, are listed in table II.

Preparation of Samples

Three groups of samples were prepared in this investigation. One group consisted of JP-4 - petrolatum mixtures (without magnesium) having the same composition as the hydrocarbon media of the magnesium slurries. In the second group, which consisted of samples composed of 50 percent magnesium powder and 50 percent medium (petrolatum plus JP-4 or o-xylene), the concentration of each of the five petrolatums was varied. The third group consisted of samples containing various concentrations of magnesium in a medium of constant composition (18 percent petrolatum E and 72 percent JP-4 by weight).

A preliminary study was made to determine the best method of incorporating petrolatum into a slurry. A series of slurry samples containing 50 percent magnesium, 18 percent petrolatum E, and 32 percent JP-4 was prepared. Some of these samples were made up by thoroughly mixing the magnesium powder with the JP-4 and then adding the petrolatum undiluted. The others were prepared by mixing the magnesium with part of the JP-4 (sufficient to wet the magnesium and make a fluid suspension) and adding the petrolatum as a 50-percent mixture in the balance of the JP-4. The samples were then vigorously stirred with a motor-driven stirrer while being heated. Some were heated to 140°-160° F, and the others were heated to reflux temperature (266°-271° F). Two samples were also prepared containing 20.3 percent petrolatum E, the petrolatum being added molten and undiluted. One of these was heated to 140°-160° F while being stirred, and the other was stirred at room temperature. From the

results of this work (see table III), the following standard procedure was adopted: the magnesium powder was weighed into a clean, tin-plated paint can (quart can for an 800-g batch; pint can for a 400-g batch), and most of the liquid hydrocarbon was added and thoroughly mixed with the magnesium. The petrolatum was then added as a 75-percent mixture in the balance of the hydrocarbon, the mixture having been prepared in advance by dissolving the petrolatum in the liquid hydrocarbon at about 175°-195° F and cooling to room temperature. (The 75-percent petrolatum mixture was used instead of the 50-percent mixture previously mentioned so that when slurries containing 30 percent petrolatum were 2941
prepared, part of the liquid hydrocarbon would be available to wet the magnesium before the petrolatum mixture was added.) The can and contents were heated to 140°-160° F on a hot plate while being stirred vigorously with a motor-driven stirrer. To minimize evaporation, the can was kept covered while being heated and stirred; after the can was removed from the hot-plate, the small weight loss due to evaporation was made up with additional liquid hydrocarbon. The can was then sealed and cooled in an 86° F water bath. The samples were aged for at least 2 weeks before they were tested because the data in table III indicate that the viscosity of these slurries increases for a short period after preparation.

The samples of petrolatum - JP-4 mixtures were prepared by a similar procedure.

Measurement of Physical Properties

Viscosities. - The viscosities of the samples were measured at both low and high rates of shear. The results are reported as apparent viscosities in centipoises since the materials were not Newtonian.

A model LVF Brookfield Synchro-lectric rotational viscometer (fig. 1) was used for measurements at low shear rates. For apparent viscosities up to 10,000 centipoises, the number 3 spindle of this instrument was run at 12 rpm (estimated shear rate, 10 reciprocal seconds), while the number 4 spindle at 6 rpm (estimated shear rate, 0.5 reciprocal second) was used for higher viscosities. The cans of material were brought to 86±1° F in a water bath, the viscometer spindle was immersed in the material, and the viscosity reading was taken after the spindle had rotated for 30±0.5 seconds. This 30-second interval was fixed arbitrarily, since the viscosity reading slowly decreased with continued rotation of the spindle. The apparent viscosity thus obtained was reported as the Brookfield apparent viscosity. With this procedure it was found that multiple readings on the same sample almost always agreed within 10 percent of the mean value. When the viscometer was tested with a 95-percent solution of glycerol in water, the mean Brookfield apparent vicosity was found to be 259 centipoises at 86° F. The viscosity, at this temperature, cited in the literature is 248 centipoises (ref. 9).

The Severs Extrusion Rheometer (fig. 1) was used to measure apparent viscosities at high rates of shear (mainly in the range of 1000 to 20,000 reciprocal seconds, depending on the characteristics of the slurry) at room temperatures. This instrument, a photograph of which is shown in reference 10, consists of a vertical cylindrical chamber containing the material to be tested, a regulator which controls the pressure of the air entering the top of the chamber, gages indicating line and controlled air pressures, and a tubular orifice at the bottom of the chamber. The orifice used in this work was 5.00 centimeters long and its inside radius was 0.0562 centimeter. The air pressure forces the material through the orifice, and when the pressure is changed stepwise, the flow of slurry through the orifice, and therefore the rate of shear, changes correspondingly. The apparent viscosity at each rate of shear was calculated from the rheometer data in the manner shown in the appendix. When a 95-percent solution of glycerol in water was tested as a standard at rates of shear ranging from 377 to 2830 reciprocal seconds, the mean viscosity was found to be 243 centipoises at 86° F.

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The residual viscosity, which has been defined in reference 11 as the apparent viscosity extrapolated to an infinite rate of shear, was found by plotting the reciprocal of the rate of shear, $1/\sigma$, against the apparent viscosity and extrapolating the data to the intercept on the apparent-viscosity axis, where $1/\sigma = 0$. This technique has been applied to suspensions of carbon in mineral oil (ref. 11) and to studies of greases (ref. 12). An example of this procedure is given in the appendix as well as typical rate of shear - shearing stress curves. Duplicate determinations of the residual viscosity on the same slurry usually have been found to agree within 10 percent of the mean.

Settling. - The settling characteristics of the slurries were determined by measuring the extent to which the magnesium settled in ordinary 50-milliliter graduated cylinders which had an internal diameter of 2 centimeters. The slurry was vigorously mixed and poured into the cylinder to approximately the 50-milliliter mark. The cylinder was then sealed and set in an 86° F water bath. As the magnesium settled, it left a layer of clear supernatant liquid which was sharply demarcated from the magnesium layer. The slurries were permitted to settle for 28 days (672 hr) or longer, and the settled height was recorded at intervals.

The extent of settling at each reading was expressed as the sedimentation ratio, which is the ratio

$$\frac{\text{grams magnesium per gram slurry before settling}}{\text{average grams magnesium per gram settled portion of slurry}}$$

The denominator was calculated from the relative volumes of the original slurry and the settled portion and from the densities of the individual components. Settling rate curves, such as those in figure 2, were obtained by plotting sedimentation ratio against time of settling. The sedimentation ratios at 2 days (48 hr), 5 days (120 hr), and 28 days (672 hr) for each sample were interpolated from such curves and tabulated.

The reproducibility of the sedimentation ratio can be judged from figure 2, which shows sedimentation ratio - time plots for five specimens from the same sample of slurry. Four of these were run simultaneously, and one was run separately. The group of four specimens agreed closely with the other specimen only toward the end of the 28-day period. Because of this, only the sedimentation ratios at 28 days are shown in plots in which slurries are compared.

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Redispersibility. - After the settling samples described previously had settled for 28 days (or longer in several instances) they were mounted on the shaker shown in figure 3. This device shook the cylinders of slurry 172 times per minute through an arc of 59° on a radius of 6 inches. After 5±0.01 minutes of shaking, the cylinders were quickly opened, inverted at an angle of 45°, and allowed to drain for 1 minute. The cylinder was then set upright for 1 minute, and the volume of material remaining in the cylinder was measured.

The percentage redispersible was calculated from the equation

$$\text{percentage redispersible} = \frac{h - h_1}{h} \times 100$$

where

h settled volume before shaking

h_1 volume remaining in cylinder after draining

Five determinations run on one sample of slurry gave the following values for the percentage redispersible: 54, 59, 58, 100, and 100 percent. It may be that in the case of the 100-percent values, the entire settled portion slipped loose as a slug. When this undesirable slippage did not occur, the results agreed very well. When it did occur, the discrepancy could be recognized, either by comparison with duplicate samples or by comparison with other samples in a series of determinations.

RESULTS AND DISCUSSION

Reproducibility of Petrolatum-Stabilized Magnesium Slurries

When petrolatum was used as a stabilizer, successive batches of slurry made from the same lots of ingredients had closely similar

Brookfield apparent viscosities. Data which will be presented later indicate that the other measured properties would therefore also be similar. The Brookfield apparent viscosity of five slurries composed of 50.0 percent magnesium, 14.0 percent petrolatum E, and 36.0 percent JP-4 ranged from 1610 to 1920 centipoises (at 86° F). The mean viscosity was 1750 centipoises, and the average deviation from the mean was 99 centipoises. Similar reproducibility was obtained with other slurries prepared in duplicate or triplicate, as shown in table III.

Physical Properties of JP-4 - Petrolatum Media

As indicated in figure 4 and in table IV, the Brookfield apparent viscosities of mixtures of JP-4 with petrolatums B or E increased exponentially with the weight percent of petrolatum concentration. It is presumed that petrolatums A, C, and D would give similar results. Not only did the Brookfield apparent viscosities differ for the two petrolatums at the same concentration, but the slopes of the apparent viscosity - concentration plots were also different.

At high rates of shear, the apparent viscosities were very much lower than at low rates of shear, as shown by a comparison of the apparent viscosities in figures 4 and 5. The apparent viscosities of the mixtures containing higher concentrations of petrolatum decreased more rapidly with increasing rate of shear, so that the extrapolated residual viscosities of three samples with 44.4, 52.0, and 60.0 percent petrolatum B were similar (fig. 5 and table IV).

The great decrease in the apparent viscosity of the petrolatum - JP-4 mixture at high rates of shear is evidence of its non-Newtonian nature. In contrast, the viscosity of a 95-percent solution of glycerol in water (a Newtonian solution) measured on the Brookfield viscometer was very similar to its viscosity measured on the Severs Rheometer (see EXPERIMENTAL section).

Factors Affecting Physical Properties of Magnesium Slurries

Method of preparation. - Table III summarizes the Brookfield apparent viscosities of slurries of like composition which were prepared by adding the petrolatum as a solid, as a melt, or as a mixture with JP-4, and mixing at various temperatures. The data indicate that a somewhat higher Brookfield apparent viscosity was obtained by adding the petrolatum as a previously prepared mixture with JP-4 and heating the slurry to 140°-160° F while stirring. The difference in viscosity between the

20.3-percent petrolatum sample which was heated to 140°-160° F (5430 centipoises) and the one which was mixed at room temperature (3480 centipoises) demonstrates the necessity of heating the slurry in order to obtain the maximum viscosity.

The data in table III also demonstrate that these slurries usually increase in Brookfield apparent viscosity for a time after they are prepared and that this increase is not uniform. However, the viscosities reached a constant level (within experimental error) within 2 weeks, and all slurries were therefore aged for 2 weeks before they were tested.

<u>Properties and concentration of petrolatum</u>. - An increase in the petrolatum concentration of a slurry increased its Brookfield apparent viscosity and its residual viscosity, and decreased its rate of settling and its redispersibility (table V).

The change in the residual and Brookfield apparent viscosities of slurries with increasing petrolatum concentration is shown in figure 6 for each petrolatum. It can be seen that the residual viscosity was much lower than the Brookfield apparent viscosity just as in the case of the petrolatum - JP-4 mixtures (fig. 4). The viscosities increased exponentially with petrolatum concentration, and in the range examined, the plot of the logarithm of viscosity against percent petrolatum in the slurry was a straight line with a slope ranging from 0.062 to 0.13, depending on the petrolatum used.

The Brookfield apparent viscosity plots in figure 6 are summarized in figure 7, which shows how greatly the viscosity obtained depended on the petrolatum which was used. The slurries prepared covered a wide range of Brookfield apparent viscosities from 160 centipoises (like thin paint) to 16,100 centipoises (like apple butter). For a given petrolatum concentration (in the concentration range tested), petrolatums C and E gave the highest Brookfield and residual viscosities, E giving higher viscosities than C over most of the range. Petrolatums A and B gave the lowest viscosities.

The residual viscosity plots in figure 6 are summarized in figure 8. The slopes of the plots and their relative order are very much like those in figure 7, which indicates that the relative values of the residual viscosities of the type of slurries under investigation can be predicted from the Brookfield apparent viscosities.

The marked difference in Brookfield apparent viscosity between a magnesium slurry and the JP-4 - petrolatum medium of the slurry can be seen in figure 9, in which the Brookfield apparent viscosity of a slurry and its medium are plotted against the petrolatum concentration in the medium.

The decrease in the extent of settling obtainable when a moderate proportion of petrolatum is incorporated into a magnesium slurry can be seen in figure 10. This figure also shows how rapidly the sedimentation ratio (after 28 days settling) increases with petrolatum concentration for slurries prepared with each of the five petrolatums. It is probably of no practical importance that a few of the slurries prepared with 14 or 18 percent petrolatum had lower sedimentation ratios than a slurry containing no petrolatum, since all the sedimentation ratios in this region are so low. For any given petrolatum concentration (in the range tested), the sedimentation ratio was greatly dependent on the petrolatum which was used. Petrolatums C and E gave the highest sedimentation ratios and B the lowest.

The redispersibility of the slurries decreased rapidly with increasing petrolatum concentration, as shown in figure 11. At any given petrolatum concentration, petrolatum C gave the lowest percentage of redispersibility, E gave a somewhat higher percentage, and A and D gave much higher percentages. While there were differences in the redispersibility of the various slurries, all could easily be remixed to their original condition by stirring when the Brookfield apparent viscosity was less than 5000 to 6000 centipoises.

<u>Aromatic content of liquid hydrocarbon</u>. - It was considered possible that the degree to which the magnesium powder was wet, and consequently the Brookfield apparent viscosity of the slurry, might be affected by the concentration of aromatic hydrocarbon in the slurry. Slurries were therefore prepared with 50 percent magnesium, various proportions of petrolatum E, and <u>o</u>-xylene (instead of JP-4). It was found that these slurries had the same Brookfield apparent viscosity and redispersibility, within experimental error, as corresponding slurries made with JP-4 (fig. 6(e) and table V). Evidently there is no difference in this respect between the use of a 100-percent-aromatic liquid hydrocarbon and JP-4 (9.8 percent aromatics by volume).

<u>Temperature</u>. - The Brookfield apparent viscosity of slurries stabilized with petrolatum was very sensitive to temperature changes (fig. 12). The Brookfield apparent viscosity of a slurry containing 50 percent magnesium and 18 percent petrolatum E changed from 150 centipoises at 118° F to 92,000 centipoises at 28° F. A slurry containing 26 percent petrolatum B showed similar behavior. This is a very undesirable characteristic from the standpoint of handling and storing the slurry over a wide range of temperatures, but it might also be useful, in that a viscous slurry which settles slowly could be thinned by warming when it is forced through the fuel system.

The effect of temperature might possibly be lessened by the addition of small proportions of materials which are used as pour-point depressants or viscosity-index improvers in lubricating oils.

Magnesium concentration. - When the ratio of petrolatum to JP-4 in the hydrocarbon medium was kept constant, increasing the magnesium concentration of a slurry increased its residual and Brookfield apparent viscosities (table VI and fig. 13(a)). In this figure, the plot of the logarithm of Brookfield apparent viscosity against magnesium concentration changes slope rather sharply at approximately 15 and 40-percent magnesium instead of being a straight line. A similar phenomenon has apparently been noted by others, since reference 13 cites the case of a pigment suspension for which a plot of the logarithm of plastic viscosity against pigment concentration changed slope and the two portions of the plot followed two different equations. This behavior may possibly be related to the degree of flocculation of the suspended particles or to the restricted movement of the particles as the suspension becomes more crowded.

The plot of the logarithm of residual viscosity against magnesium concentration in figure 13(a) is a smooth curve in contrast to the straight line obtained when the petrolatum concentration is varied (fig. 8).

The sedimentation ratio increased linearly with magnesium concentration in the range investigated (fig. 13(b)). When the concentration of the same petrolatum (E) was varied in slurries containing 50 percent magnesium, the change in the sedimentation ratio was not linear (fig. 10). An increase in magnesium concentration from 40 to 60 percent increased the sedimentation ratio approximately as much as increasing the concentration of petrolatum E in a 50-percent-magnesium slurry from 18 to 30 percent.

Another effect of increasing the magnesium concentration was to decrease the redispersibility of the slurries, as is shown in figure 13(c). A smooth, inverted S-shape plot is shown, although the duplicate determinations of the redispersibility of the slurry containing 60 percent magnesium seem inconsistent with the measurements at other concentrations.

Comparison of Slurries of Various Compositions at the Same Brookfield Apparent Viscosity

Since the reason for adding petrolatum to a slurry is to increase its viscosity at a low rate of shear so as to retard the settling of the magnesium, it is of interest to compare the characteristics of the slurries at the same Brookfield apparent viscosity, regardless of whether this viscosity is controlled by the concentration of petrolatum or of magnesium.

Constant magnesium concentration in media of various compositions. - The properties of slurries containing 50 percent magnesium and various concentrations of the five petrolatums are shown in figure 14, in which the Brookfield apparent viscosity is plotted against residual viscosity, sedimentation ratio, and percentage redispersible. The residual viscosity increased with increasing Brookfield apparent viscosity over the range investigated (fig. 14(a)). For a given Brookfield apparent viscosity, petrolatum C appears to give the lowest (best) residual viscosity, and B the highest. The sedimentation ratio after 28 days settling increased with increasing Brookfield apparent viscosity (fig. 14(b)). Petrolatums A and E gave the highest (best) sedimentation ratio, while C gave the lowest. The redispersibility decreased as the Brookfield apparent viscosity increased (fig. 14(c)). It was highest (best) when petrolatum A or D was used, lowest when C was used (over most of the viscosity range).

Various magnesium concentrations in medium of fixed composition compared with 50 percent magnesium in media of various compositions. - The physical characteristics of two series of slurries, one series containing 50 percent magnesium and the other containing a range of magnesium concentrations, are compared in figure 15. The residual viscosities of the two series were almost identical for corresponding Brookfield apparent viscosities (fig. 15(a)), while the sedimentation ratios and redispersibilities were somewhat higher for the series with varying magnesium concentration over most of the range in which the Brookfield apparent viscosities overlapped (figs. 15(b) and 15(c)).

These comparisons indicate that equally desirable or even slightly better slurry characteristics can be obtained by increasing the magnesium concentration above 50 percent and decreasing the petrolatum concentration below that required for a slurry containing 50 percent magnesium. For example, a slurry containing 65 percent magnesium and 14 percent petrolatum E had almost the same Brookfield and residual viscosities, almost the same redispersibility, and a somewhat higher sedimentation ratio than a slurry containing 50 percent magnesium and 20.5 percent petrolatum E (fig. 15). This suggests that the increased thrust obtainable from a higher magnesium concentration need not entail a sacrifice in the physical characteristics of the slurry, although no combustor data are available to substantiate this idea.

Choice of Most Suitable Petrolatum and Concentration of Petrolatum

The most desirable petrolatum would be the one which at the lowest concentration gives a slurry with the highest sedimentation ratio, lowest residual viscosity, and greatest redispersibility, and at the same time a convenient Brookfield apparent viscosity. The latter should probably not exceed 10,000 centipoises to avoid difficulties in handling. Since some of these requirements are contradictory, it is believed that more emphasis should be placed on the highest sedimentation ratio which can be attained with a minimum petrolatum concentration and a convenient Brookfield apparent viscosity.

Because it was not found possible to establish a quantitative correlation between the measured properties of the petrolatum and those of the slurries, the slurries containing 50 percent magnesium and stabilized with the five petrolatums have been compared in a rating chart (table VII). In this rating chart, more weight is given to the Brookfield apparent viscosity and sedimentation ratio than to the other properties. 2941
In each respect considered, the best petrolatum is rated as 1, and the poorer ones are rated with successively higher numbers. The lowest sum of ratings then indicates the most desirable petrolatum. Where two or more petrolatums are given the same rating in a given respect, they appear to be equal within experimental error. In those cases where one petrolatum is more satisfactory than another for a given property over only part of the range investigated, preference is given to the petrolatum giving the better slurry over the greater part of the desirable range of the property in question.

The rating chart shows that no one petrolatum gives a slurry which is best in all respects, and a compromise must therefore be made in choosing a petrolatum. Petrolatum B is obviously the least desirable. The stiffer, higher melting, darker petrolatums C, D, and E have a small margin of superiority over A, which like B, is softer, lower melting, lighter, and less viscous. Among the dark petrolatums, E appears to be better than C or D.

Among the slurries containing 50 percent magnesium, those stabilized with 18 to 25 percent petrolatum C, D, or E appear to have promise as aircraft fuels. This range of concentration of petrolatum E gave a slurry with a Brookfield apparent viscosity ranging approximately from 2600 to 10,000 centipoises at 86° F. The sedimentation ratio after 28 days settling was 0.750 to 0.900, the residual viscosities were 50 to 135 centipoises, and the redispersibility ranged from 39 to 10 percent. If petrolatum C were used instead, somewhat more would be required, and the settling and redispersibility would be poorer, but the residual viscosity would be a little better. Even more of petrolatum D would be required, but with some improvement in residual viscosity and redispersibility and a small sacrifice in settling.

It is presumed that in slurries containing more than 50 percent magnesium, petrolatums C, D, and E would still be the most satisfactory, and that petrolatum E would again be more desirable than C or D.

SUMMARY OF RESULTS

In a study of the physical properties of magnesium-hydrocarbon slurry fuels made with 18-micron magnesium powder, the following results were obtained:

1. The settling of magnesium - JP-4 slurry fuel containing 50 percent magnesium can be greatly retarded by the incorporation of a moderate proportion of petrolatum so as to increase the viscosity of the slurry. Slurries with similar physical characteristics can be obtained by incorporating more than 50 percent magnesium and decreasing the proportion of petrolatum.

2. When petrolatum was used as a stabilizer, successive batches of magnesium slurry made from the same batches of ingredients had closely similar physical characteristics.

3. No one of the five petrolatums tested gave a slurry which was best in all respects, but for slurries containing 50 percent magnesium the incorporation of 18 to 25 percent petrolatum E, which is one of the higher-melting, more viscous, stiffer, and darker petrolatums of those tested, appeared to offer the most satisfactory product.

4. The maximum Brookfield apparent viscosity was obtained when

a. The petrolatum was first heated to 175° to 195° F with part of the JP-4.

b. The combined slurry components were vigorously stirred at 140° to 160° F.

c. The slurries were aged for at least 2 weeks.

5. In the range of petrolatum concentrations investigated, the Brookfield apparent viscosity of slurries containing 50 percent magnesium increased exponentially with the petrolatum concentration, but the rate of increase was different for each petrolatum. This was also true for petrolatum - JP-4 mixtures containing no magnesium.

6. The substitution of an aromatic hydrocarbon for JP-4 in slurries containing petrolatum E and 50 percent magnesium had no measurable effect on the Brookfield apparent viscosity of the slurry.

7. The Brookfield apparent viscosity of slurries in which the composition of the medium was held constant increased with increasing magnesium concentration. The rate of increase was greatest in the ranges of 0 to 15 percent and 40 to 65 percent magnesium (maximum concentration investigated).

8. The residual viscosity of the slurries which were prepared was far lower than the Brookfield apparent viscosity, but showed a similar dependence on magnesium concentration, petrolatum concentration, and the properties of the petrolatum.

9. The residual viscosity of the slurries which were prepared increased with the Brookfield apparent viscosity, and when the same petrolatum was used, the relation of the two viscosities was the same regardless of whether the viscosity was controlled by the petrolatum concentration or the magnesium concentration. 2941

10. The sedimentation ratio of slurries containing 50 percent magnesium (after 28 days settling) increased greatly with increasing petrolatum concentration and increasing magnesium concentration within the range investigated.

11. The sedimentation ratio (after 28 days settling) of petrolatum-stabilized slurries increased almost exponentially with increasing Brookfield apparent viscosity. The sedimentation ratio was somewhat higher when the viscosity was controlled by the magnesium concentration than when it was controlled by the petrolatum concentration, in the range of 1500 to 4100 centipoises. The latter comparison was made on slurries prepared with only one petrolatum.

12. The redispersibility of slurries decreased both with increasing magnesium concentration and with increasing petrolatum concentration.

13. The redispersibility of slurries decreased with increasing Brookfield apparent viscosity. The redispersibility was essentially independent of whether the viscosity was controlled by the petrolatum concentration or the magnesium concentration, in the range of 1500 to 4500 centipoises. The latter comparison was made on slurries prepared with only one petrolatum.

14. The Brookfield apparent viscosity of petrolatum-stabilized slurry fuels increased very rapidly with decreasing temperature over the range investigated (118° to 28° F).

CONCLUDING REMARKS

The data obtained indicate that slurries of 18-micron atomized magnesium powder in JP-4 can be stabilized sufficiently by the addition of petrolatum to offer promise for use as aircraft fuels. These slurries, which are easily prepared, can be remixed to their original condition after settling has occurred. Their principal disadvantage seems to be the great increase in viscosity with decreasing temperature.

In preparing petrolatum-stabilized slurries, a compromise must be struck between slight settling and the difficult handling problems because of the high viscosity resulting from the use of high concentrations of petrolatum (e.g., 30 percent or more petrolatum E) and rapid settling and the less difficult handling problems when little petrolatum is used.

The petrolatum-stabilized slurries which have been discussed could possibly be improved by the incorporation of small quantities of materials to reduce the effect of temperature on viscosity. The addition of surface-active materials which might further retard the settling by improving the dispersion of the magnesium powder may also be helpful.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 15, 1953

APPENDIX - CALCULATIONS BASED ON DATA OBTAINED WITH SEVERS EXTRUSION RHEOMETER

The calculations are based on the following equations (ref. 11):

$$\text{Shearing stress} = \frac{Pr}{2L}, \text{ lb/sq in.}$$

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$$\text{Rate of shear, } \sigma = \frac{4Q}{\pi r^3}, \text{ sec}^{-1}$$

where

$$Q = \frac{M}{\rho t}$$

$$\text{Apparent viscosity, } \eta = \left(\frac{\text{shearing stress, lb/sq in.}}{\text{rate of shear, sec}^{-1}}\right)(6.85\times10^6), \text{ centipoises}$$

$$= \left(\frac{Pr}{2L}\right)\left(\frac{1}{\sigma}\right)(6.85\times10^6)$$

where

- P applied air pressure plus hydrostatic pressure, lb/sq in.
- r radius of orifice (0.0562 cm for orifice which was used), cm
- L length of orifice (5.00 cm for orifice which was used), cm
- Q volume rate of flow of slurry through orifice, $M/\rho t$, cc/sec
- M weight of slurry flowing through orifice in t seconds, g
- ρ density of slurry, g/cc

For example, when a slurry composed of 50.0 percent magnesium, 22.2 percent petrolatum D, and 27.8 percent JP-4 was poured into the cylinder to a depth of 5 inches, and a gage pressure of 2.0 lb/sq in. was applied, 18.6 grams of slurry passed through the orifice in 105.0 seconds.

Calculated density of slurry = 1.106 g/cc

Calculated hydrostatic pressure = 0.20 lb/sq in.

Total pressure applied, P, = 0.20 + 2.0 = 2.20 lb/sq in.

$$Q = \frac{M}{\rho t} = \frac{18.6}{1.106(105.0)} = 0.1602 \text{ cc/sec}$$

$$\sigma = \frac{4Q}{\pi r^3} = \frac{4(0.1602)}{\pi(0.0562)^3} = 1097 \text{ sec}^{-1}$$

$$\frac{1}{\sigma} = 91.16\times10^{-5} \text{ sec}$$

$$\frac{Pr}{2L} = \frac{2.20(0.0562)}{2(5.00)} = 0.01236 \text{ lb/sq in.}$$

$$\eta = \left(\frac{Pr}{2L}\right)\left(\frac{1}{\sigma}\right)(6.85\times10^6) = (0.01236)(91.16\times10^{-5})(6.85\times10^6) = 77.2 \text{ centipoises}$$

The data obtained with the Severs Rheometer and the apparent viscosities calculated from them, together with the calculated slurry densities, rates of shear, reciprocals of rate of shear, and shearing stresses are listed in table VIII.

Figure 16 shows how the reciprocals of the rate of shear were plotted against apparent viscosity and extrapolated to give the residual viscosity of a slurry. The residual viscosity of each slurry, as listed in tables V and VI, was determined in this way. Further information as to the rheological characteristics of slurries can be obtained by plotting the rate of shear against the shearing stress. Such a plot for three 50-percent-magnesium slurries stabilized with petrolatum D is shown in figure 17.

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TABLE I. - PROPERTIES OF LIQUID HYDROCARBONS

USED IN PREPARATION OF SAMPLES

Properties	MIL-F-5624A, grade JP-4	o-Xylene
Boiling point, °F		291.72
Distillation range, °F		
Initial boiling point	140	
Percent evaporated		
5	199	
10	222	
20	248	
30	268	
40	286	
50	300	
60	325	
70	348	
80	382	
90	427	
95	459	
Final boiling point	488	
Residue, percent	1	
Freezing point, °F		-15.36
Purity (from freezing point), percent		97.6+
Reid vapor pressure, lb/sq in.	2.5	
Specific gravity, 60/60° F	0.768	
Density at 68° F, g/ml		0.8765
Hydrogen-carbon ratio	0.169	
Heat of combustion, Btu/lb	18,675	
Aromatics (silica gel), percent by volume	9.8	
Aniline point, °F	134.6	
Bromine number	1.2	
Refractive index, n_D 68° F		1.5024

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TABLE II. - PHYSICAL PROPERTIES OF PETROLATUMS USED IN

STABILIZATION OF MAGNESIUM SLURRIES

Petrolatum	A.S.T.M. melting point, °F	Saybolt viscosity at 210° F, sec	A.S.T.M. penetration at 77° F, tenths of millimeters	Specific gravity, 60/60° F	Color
A	121	66	220	0.864	Amber
B	121	68	191	[a].865	Amber
C	141	91	111	.871	Dark brown
D	145	65	215	.871	Dark green
E	161	101	80	[a].871	Dark green

[a]Estimated.

TABLE III. - EFFECT OF METHOD OF PREPARATION ON BROOKFIELD APPARENT VISCOSITY OF SLURRIES

[Slurry composition: magnesium powder, 50.0 percent; JP-4 plus petrolatum E, 50.0 percent.]

Petrolatum, percent by weight	Petrolatum added as -	Mixing temperature, °F	Viscosity within 24 hours, centipoises	Viscosity after aging at least 14 days, centipoises
18.0	100 percent, solid	140-160	2020	2860
18.0	100 percent, solid	140-160	2200	2900
			mean = 2110	mean = 2880
18.0	100 percent, solid	266-271(reflux)	1550	2300
18.0	100 percent, solid	266-270(reflux)	1560	2500
18.0	100 percent, solid	266-268(reflux)	1870	2440
			mean = 1660	mean = 2410
18.0	50 percent, in JP-4	140-160	2970	3400
18.0	50 percent, in JP-4	140-160	2470	2640
18.0	50 percent, in JP-4	140-160	2440	3350
			mean = 2630	mean = 3130
20.3	100 percent, molten	140-160	5530	5430
20.3	100 percent, molten	room temperature 80-86	2670	3480

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TABLE IV. - SUMMARY OF DATA ON PETROLATUM - JP-4 MIXTURES

CONTAINING NO MAGNESIUM

Petrolatum	Petrolatum, percent by weight	JP-4, percent by weight	Brookfield apparent viscosity at 86° F, centipoises	Residual viscosity at 79°-81° F, centipoises
B	28.0	72.0	10	--
	36.0	64.0	30	--
	44.4	55.6	100	8
	52.0	48.0	490	14
	60.0	40.0	1680	25
E	28.0	72.0	10	--
	36.0	64.0	95	--
	44.0	55.6	420	--
	52.0	48.0	3500	--

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TABLE V. - SUMMARY OF TEST DATA ON PETROLATUM-STABILIZED MAGNESIUM-HYDROCARBON[a] SLURRIES CONTAINING 50 PERCENT MAGNESIUM POWDER AND VARIOUS CONCENTRATIONS OF FIVE PETROLATUMS

Petrolatum	Petrolatum concentration, percent by weight	Brookfield apparent viscosity at 86° F, centipoises (b)	Residual viscosity at 75°-86° F, centipoises	Sedimentation ratio at 86° F after -			Percentage redispersible
				2 days	5 days	28 days	
A	14.0	200	---	-----	-----	-----	---
	18.0	530	23	0.807	0.785	0.755	100
	22.2	2,250	---	-----	-----	-----	---
	25.9	2,950	52	.982	.960	.843	88
	30.0	5,900	107	.986	.974	.923	34
B	14.0	160	---	-----	-----	-----	---
	14.0	210	---	-----	-----	-----	---
	18.0	350	20	0.753	0.747	0.734	97
	22.2	1,280	36	.858	.810	.771	97
	25.9	3,150	---	-----	-----	-----	---
	25.9	2,860	64	.935	.880	.805	30
	30.0	5,420	290	.985	.971	.897	0
C	14.0	515	13	0.804	0.761	0.727	30
	18.0	2,490	32	.949	.908	.799	34
	22.2	5,400	85	.985	.972	.917	3
	25.9	16,100	144	.986	.976	.930	2
D	14.0	450	---	-----	-----	-----	---
	18.0	1,300	25	0.831	0.787	0.776	100
	22.2	3,200	50	.929	.860	.806	96
	25.9	6,070	75	.982	.957	.870	69
	30.0	10,000	---	.985	.965	.895	48
E	10.0	870	---	-----	-----	-----	---
	10.0	520	---	0.801	0.781	0.767	60[c]
	14.0	1,920	---	-----	-----	-----	---
	14.0	1,700	---	-----	-----	-----	---
	14.0	1,800	---	-----	-----	-----	---
	14.0	1,720	---	-----	-----	-----	---
	14.0	1,610	28	0.928	0.869	0.802	54[c]
	18.0	3,400	---	-----	-----	-----	---
	18.0	2,640	---	.957	.902	.816	39[c]
	18.0	3,350	58	-----	-----	-----	---
	22.2	5,080	86	.985	.964	.865	17
	25.9	11,100	160	.997	.991	.946	2
	30.0	16,000	238	-----	-----	-----	---
E[d]	14.0	1,570	---	-----	-----	-----	49[c]
	18.0	3,000	---	-----	-----	-----	---
	22.2	5,030	---	-----	-----	-----	16[c]
	25.9	10,200	---	-----	-----	-----	0[c]
	30.0	12,500	---	-----	-----	-----	---
None	0	145	---	.780	.775	.767	100

[a]Liquid hydrocarbon was MIL-F-5624A, grade JP-4 unless otherwise noted.
[b]Mean of two or more determinations.
[c]After 44 days' settling.
[d]Liquid hydrocarbon was o-xylene.

TABLE VI. - SUMMARY OF TEST DATA ON PETROLATUM-STABILIZED MAGNESIUM - JP-4 SLURRIES CONTAINING VARIOUS CONCENTRATIONS OF MAGNESIUM 2941

[Composition of medium: 28 percent petrolatum E; 72 percent MIL-F-5624A, grade JP-4 fuel.]

Magnesium concentration, percent by weight	Brookfield apparent viscosity at 86° F, centipoises (a)	Residual viscosity at 79°-82° F, centipoises	Sedimentation ratio at 86° F after -			Percentage redispersible
			2 days	5 days	28 days	
10	50	--	-----	-----	-----	---
10	60	--	-----	-----	-----	---
12.5	245	--	-----	-----	-----	---
15	360	--	-----	-----	-----	---
17.5	372	--	-----	-----	-----	---
20	420	10	-----	-----	-----	100
40	500	--	-----	-----	-----	---
40	560	14	0.729	0.720	0.708	94
50	1610	28	.928	.869	.802	54
50	1700	--	-----	-----	-----	---
50	1720	--	-----	-----	-----	---
50	1800	--	-----	-----	-----	---
50	1920	--	-----	-----	-----	---
55	1770	30	.930	.878	.822	36
55	2550	--	-----	-----	-----	44
60	2480	41	.939	.898	.861	48
60	3860	--	-----	-----	-----	50
65	4100	77	.951	.927	.893	---
65	4580	--	-----	-----	-----	28

[a]Mean of two or more determinations.

TABLE VII. - RATING CHART FOR PETROLATUMS[a]

[Petrolatum making the best slurry in each respect rated as 1. Poorer petrolatums rated with successively higher numbers. Equal rating given to two or more petrolatums in a given respect indicates that they seem to be alike within experimental error. In those cases where one petrolatum is more satisfactory than another for a given property over only part of the range investigated, preference is given to the petrolatum giving the better slurry over the greater part of the desirable range of the property in question.]

Petrolatum	At a given petrolatum concentration:		At a given Brookfield apparent viscosity:			Sum of ratings
	Brookfield apparent viscosity (a)	Sedimentation ratio at 4 weeks (b)	Residual viscosity (c)	Sedimentation ratio at 4 weeks (d)	Redispersibility (e)	
A	4	4	3	1	2	14
B	4	5	4	3	4	20
C	2	2	1	4	5	14
D	3	3	2	4	1	13
E	1	1	3	2	3	10

[a]From fig. 7.
[b]From fig. 10.
[c]From fig. 14(a).
[d]From fig. 14(b).
[e]From fig. 14(c).

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TABLE VIII. - SUMMARY OF SEVERS EXTRUSION RHEOMETER DATA AND CALCULATED RATE OF SHEAR, SHEARING STRESS, AND APPARENT VISCOSITY OF MAGNESIUM - JP-4 SLURRIES STABILIZED WITH FIVE PETROLATUMS, OF PETROLATUM - JP-4 MIXTURES, AND OF GLYCEROL-WATER

Pressure, P, lb/sq in.	Weight of material extruded, M, g	Time required to extrude M grams, t, sec	Volume rate of extrusion, Q, cc/sec (a)	Rate of shear, σ, sec^{-1} (a)	Reciprocal of rate of shear, $1/\sigma$, sec (a)	Shearing stress, $\frac{Pr}{2l}$, psi (a)	Apparent viscosity, η, centipoises
Magnesium, 50.0 percent; petrolatum A, 18.0 percent; JP-4, 32.0 percent; density, 1.096 g/cc; temperature, 82° F							
2.4	24.9	41.30	0.5502	3,769	26.53×10^{-5}	0.01349	24.5
4.2	25.4	21.60	1.073	7,350	13.61	.02360	22.0
6.0	30.5	19.57	1.422	9,741	10.27	.03372	23.7
9.0	35.4	14.51	2.226	15,250	6.558	.05058	22.7
12.1	34.2	11.00	2.836	19,430	5.147	.06800	24.0
15.1	35.2	9.28	3.461	23,700	4.218	.08486	24.5
Magnesium, 50.0 percent; petrolatum A, 25.9 percent; JP-4, 24.1 percent; density, 1.110 g/cc; temperature, 82° F							
2.3	13.6	100.6	0.1218	834.3	119.9×10^{-5}	0.01293	106
4.2	13.5	44.00	.2764	1,893	52.83	.02360	85.4
6.0	14.7	29.49	.4491	3,076	32.51	.03372	75.1
9.0	14.9	17.89	.7503	5,140	19.46	.05058	67.4
12.1	19.1	15.98	1.078	7,384	13.54	.06800	63.1
15.0	19.0	11.92	1.436	9,837	10.17	.08430	58.7
Magnesium, 50.0 percent; petrolatum A, 30.0 percent; JP-4, 20.0 percent; density, 1.091 g/cc; temperature, 84° F							
2.4	8.4	114.8	0.06709	459.6	217.6×10^{-5}	0.01349	201
4.3	9.3	58.30	.1462	1,001	99.90	.02417	165
6.0	9.4	29.90	.2882	1,974	50.66	.03372	117
9.0	11.0	24.37	.4137	2,834	35.29	.05058	122
12.0	13.2	20.61	.5869	4,020	24.88	.06744	115
15.0	12.8	14.44	.8127	5,567	17.96	.08430	104
Magnesium, 50.0 percent; petrolatum B, 18.0 percent; JP-4, 32.0 percent; density, 1.096 g/cc; temperature, 75° F							
1.2	14.6	55.29	0.2409	1,650	60.61×10^{-5}	0.006744	28.0
2.2	13.5	26.90	.4579	3,137	31.88	.01236	27.0
3.1	15.4	18.45	.7616	5,217	19.17	.01742	22.9
4.1	18.4	15.99	1.050	7,192	13.90	.02304	22.0
5.0	19.7	13.36	1.345	9,213	10.85	.02810	20.9
Magnesium, 50.0 percent; petrolatum B, 22.2 percent; JP-4, 27.8 percent; density, 1.104 g/cc; temperature, 77° F							
1.2	14.8	134.2	0.09989	684.2	146.2×10^{-5}	0.006744	67.5
3.2	17.5	44.64	.3551	2,432	41.12	.01798	50.6
5.0	19.9	26.93	.6694	4,585	21.81	.02810	42.0
7.0	23.3	21.79	.9686	6,635	15.07	.03934	40.6
10.0	26.1	15.05	1.571	10,761	9.293	.05620	35.8
Magnesium, 50.0 percent; petrolatum B, 25.9 percent; JP-4, 24.1 percent; density, 1.110 g/cc; temperature, 77° F							
2.5	12.5	113.1	0.09957	682.1	146.6×10^{-5}	0.01405	141
4.3	13.2	58.61	.2029	1,390	71.94	.02417	119
7.1	17.1	30.72	.5015	3,435	29.11	.03990	79.6
10.1	18.5	21.97	.7586	5,196	19.25	.05620	74.1
14.0	19.8	15.65	1.140	7,809	12.81	.07868	69.0
Magnesium, 50.0 percent; petrolatum B, 30.0 percent; JP-4, 20.0 percent; density, 1.117 g/cc; temperature, 75° F							
3.2	6.1	205.3	0.02660	182.2	548.8×10^{-5}	0.01798	676
5.0	8.3	121.4	.06121	419.3	238.5	.02810	459
7.0	12.3	112.1	.09823	672.9	148.6	.03934	400
9.0	17.1	117.7	.1301	891.2	112.2	.05058	389
12.0	21.5	96.89	.1987	1,361	73.48	.06744	339

[a]Only three figures are significant, although more are shown to facilitate calculation.

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TABLE VIII. - Continued. SUMMARY OF SEVERS EXTRUSION RHEOMETER DATA AND CALCULATED RATE OF SHEAR, SHEARING STRESS, AND APPARENT VISCOSITY OF MAGNESIUM - JP-4 SLURRIES STABILIZED WITH FIVE PETROLATUMS, OF PETROLATUM - JP-4 MIXTURES, AND OF GLYCEROL-WATER

Pressure, P, lb/sq in.	Weight of material extruded, M, g	Time required to extrude M grams, t, sec	Volume rate of extrusion, Q, cc/sec (a)	Rate of shear, σ, sec^{-1} (a)	Reciprocal of rate of shear, 1/σ, sec (a)	Shearing stress, $\frac{Pr}{2l}$, psi (a)	Apparent viscosity, η, centipoises
Magnesium, 50.0 percent; petrolatum C, 14.0 percent; JP-4, 36.0 percent; density, 1.090 g/cc; temperature, 84° F							
1.4	35.8	64.80	0.5069	3,472	28.80×10^{-5}	0.007868	15.5
2.3	38.1	38.29	.9129	6,253	15.99	.01293	14.2
3.2	33.5	23.72	1.296	8,878	11.26	.01798	13.9
4.1	37.7	20.76	1.666	11,412	8.763	.02304	13.8
6.0	35.3	13.47	2.404	16,467	6.073	.03372	14.0
Magnesium, 50.0 percent; petrolatum C, 18.0 percent; JP-4, 32.0 percent; density, 1.098 g/cc; temperature, 84° F							
2.3	22.5	71.77	0.2855	1,956	51.12×10^{-5}	0.01293	45.3
4.1	23.1	34.62	.6077	4,163	24.02	.02304	37.9
6.0	24.4	23.43	.9485	6,497	15.39	.03372	35.6
8.0	24.3	16.95	1.306	8,946	11.18	.04496	34.4
10.0	29.3	16.08	1.659	11,360	8.800	.05620	33.9
Magnesium, 50.0 percent; petrolatum C, 22.2 percent; JP-4, 27.8 percent; density, 1.106 g/cc; temperature, 84° F							
2.0	18.2	185.2	0.08885	608.6	164.3×10^{-5}	0.01124	126
4.2	18.3	77.49	.2135	1,462	68.40	.02360	111
6.0	18.0	46.04	.3535	2,421	41.31	.03372	95.4
9.0	20.6	30.39	.6129	4,198	23.82	.05058	82.5
12.0	23.2	23.28	.9010	6,172	16.20	.06744	74.8
Magnesium, 50.0 percent; petrolatum C, 25.9 percent; JP-4, 24.1 percent; density, 1.113 g/cc; temperature, 86° F							
5.1	14.9	129.0	0.1038	711.0	140.6×10^{-5}	0.02866	276
8.0	16.0	68.03	.2113	1,447	69.11	.04496	213
11.0	16.8	45.21	.3339	2,287	43.73	.06182	185
14.0	18.3	34.82	.4722	3,235	30.91	.07868	167
17.1	19.0	27.71	.6161	4,220	23.70	.09610	156
Magnesium, 50.0 percent; petrolatum D, 18.0 percent; JP-4, 32.0 percent; density, 1.098 g/cc; temperature, 82° F							
2.3	25.1	46.58	0.4908	3,362	29.74×10^{-5}	0.01293	26.3
4.2	24.3	23.74	.9322	6,386	15.66	.02360	25.3
6.0	26.9	17.43	1.406	9,631	10.38	.03372	24.0
9.0	30.5	13.91	1.997	13,679	7.310	.05058	25.3
12.0	32.8	15.95	1.873	12,830	7.794	.06744	36.0
Magnesium, 50.0 percent; petrolatum D, 22.2 percent; JP-4, 27.8 percent; density, 1.106 g/cc; temperature, 82° F							
2.2	18.6	105.0	0.1602	1,097	91.16×10^{-5}	0.01236	77.2
4.2	21.0	50.03	.3795	2,600	38.46	.02360	62.2
6.0	24.4	37.11	.5945	4,072	24.56	.03372	56.7
9.0	34.9	33.29	.9479	6,493	15.40	.05058	53.4
12.0	26.1	17.73	1.331	9,117	10.97	.06744	50.7
15.2	26.8	13.70	1.769	12,118	8.252	.08542	49.3
Magnesium, 50.0 percent; petrolatum D, 25.9 percent; JP-4, 24.1 percent; density, 1.113 g/cc; temperature, 84° F							
2.3	12.6	109.3	0.1036	709.7	140.9×10^{-5}	0.01293	125
4.2	13.1	50.74	.2320	1,589	62.93	.02360	102
6.1	14.5	35.36	.3684	2,524	39.62	.03428	93.0
9.1	14.7	22.33	.5915	4,052	24.68	.05114	86.5
12.0	15.1	16.68	.8134	5,572	17.95	.06744	82.9
15.0	16.5	13.90	1.067	7,309	13.68	.08430	79.0

[a]Only three figures are significant, although more are shown to facilitate calculation.

[redacted]

TABLE VIII. - Continued. SUMMARY OF SEVERS EXTRUSION RHEOMETER DATA AND CALCULATED RATE OF SHEAR, SHEARING STRESS, AND APPARENT VISCOSITY OF MAGNESIUM - JP-4 SLURRIES STABILIZED WITH FIVE PETROLATUMS, OF PETROLATUM - JP-4 MIXTURES, AND OF GLYCEROL-WATER

Pressure, P, lb/sq in.	Weight of material extruded, M, g	Time required to extrude M grams, t, sec	Volume rate of extrusion, Q, cc/sec (a)	Rate of shear, σ, sec^{-1} (a)	Reciprocal of rate of shear, $1/\sigma$, sec (a)	Shearing stress, $\frac{Pr}{2l}$, psi (a)	Apparent viscosity, η, centipoises
Magnesium, 50.0 percent; petrolatum E, 14.0 percent; JP-4, 36.0 percent; density 1.090 g/cc; temperature, 81° F; equivalent to 50 percent magnesium, 50 percent medium of 28 percent petrolatum E and 72 percent JP-4							
2.1	29.3	62.54	0.4298	2,944	33.97×10^{-5}	0.01180	27.5
4.1	23.1	23.85	.8886	6,087	16.43	.02304	25.9
6.0	26.1	20.17	1.187	8,131	12.30	.03372	28.4
Magnesium, 50.0 percent; petrolatum E, 18.0 percent; JP-4, 32.0 percent; density, 1.098 g/cc; temperature, 81° F							
1.0	5.9	180.7	0.02974	203.7	490.9×10^{-5}	0.005620	189
2.1	15.3	73.87	.1886	1,292	77.40	.01180	62.6
4.1	12.4	42.27	.2672	1,830	54.64	.02304	86.2
5.0	18.1	46.58	.3539	2,424	41.25	.02810	79.4
7.0	10.0	16.78	.5428	3,718	26.90	.03934	72.5
9.0	18.5	22.78	.7396	5,066	19.74	.05058	68.4
12.0	26.2	22.12	1.079	7,391	13.53	.06744	62.5
Magnesium, 50.0 percent; petrolatum E, 22.2 percent; JP-4, 27.8 percent; density, 1.106 g/cc; temperature, 82° F							
4.3	12.8	153.8	0.07525	515.5	194.0×10^{-5}	0.02417	321
6.1	16.1	101.0	.1441	987.1	101.3	.03428	238
9.0	15.6	56.87	.2480	1,699	58.86	.05058	204
12.0	17.4	42.88	.3669	2,513	39.79	.06744	184
15.0	15.8	28.76	.4967	3,402	29.39	.08430	170
17.9	15.3	21.92	.6311	4,323	23.13	.1006	159
21.0	23.8	27.81	.7738	5,301	18.86	.1180	152
Magnesium, 50.0 percent; petrolatum E, 25.9 percent; JP-4, 24.1 percent; density, 1.113 g/cc; temperature, 82° F							
10.2	17.8	76.89	0.2080	1,425	70.18×10^{-5}	0.05732	276
14.0	20.7	92.96	.2001	1,371	72.94	.07868	393
17.0	18.3	61.79	.2661	1,823	54.85	.09554	359
20.0	23.5	61.85	.3414	2,339	42.75	.1124	328
21.6	17.4	40.76	.3835	2,627	38.07	.1214	316
Magnesium, 50.0 percent; petrolatum E, 30.0 percent; JP-4, 20.0 percent; density, 1.118 g/cc; temperature, 84° F							
4.1	5.6	122.2	0.04099	280.8	356.1×10^{-5}	0.02304	562
6.1	10.4	125.3	.07424	508.5	196.7	.03428	462
9.1	16.9	111.3	.1358	930.2	107.5	.05114	377
12.0	24.9	113.7	.1959	1,342	74.52	.06744	344
17.0	20.5	57.87	.3169	2,171	46.06	.09554	302
Magnesium, 20.0 percent; 80.0 percent medium consisting of 28 percent petrolatum E and 72 percent JP-4; density, 1.015 g/cc; temperature, 79° F							
2.3	35.6	30.04	1.333	9,131	10.95×10^{-5}	0.01293	9.70
3.2	35.7	22.30	1.801	12,340	8.106	.01798	9.98
4.1	36.1	17.36	2.339	16,020	6.241	.02304	9.85
6.0	31.0	10.43	3.343	22,900	4.367	.03372	10.1
8.0	27.5	7.25	4.267	29,230	3.421	.04496	10.5
Magnesium, 40.0 percent; 60.0 percent medium consisting of 28 percent petrolatum E and 72 percent JP-4; density, 0.889 g/cc; temperature, 81° F							
2.2	43.4	47.01	0.9096	6,231	16.05×10^{-5}	0.01236	13.6
3.2	36.8	28.19	1.286	8,809	11.35	.01798	14.0
4.1	37.2	21.90	1.674	11,470	8.721	.02304	13.8
5.0	44.2	20.95	2.079	14,240	7.022	.02810	13.5
6.0	50.6	20.02	2.490	17,060	5.863	.03372	13.5

[a]Only three figures are significant, although more are shown to facilitate calculation.

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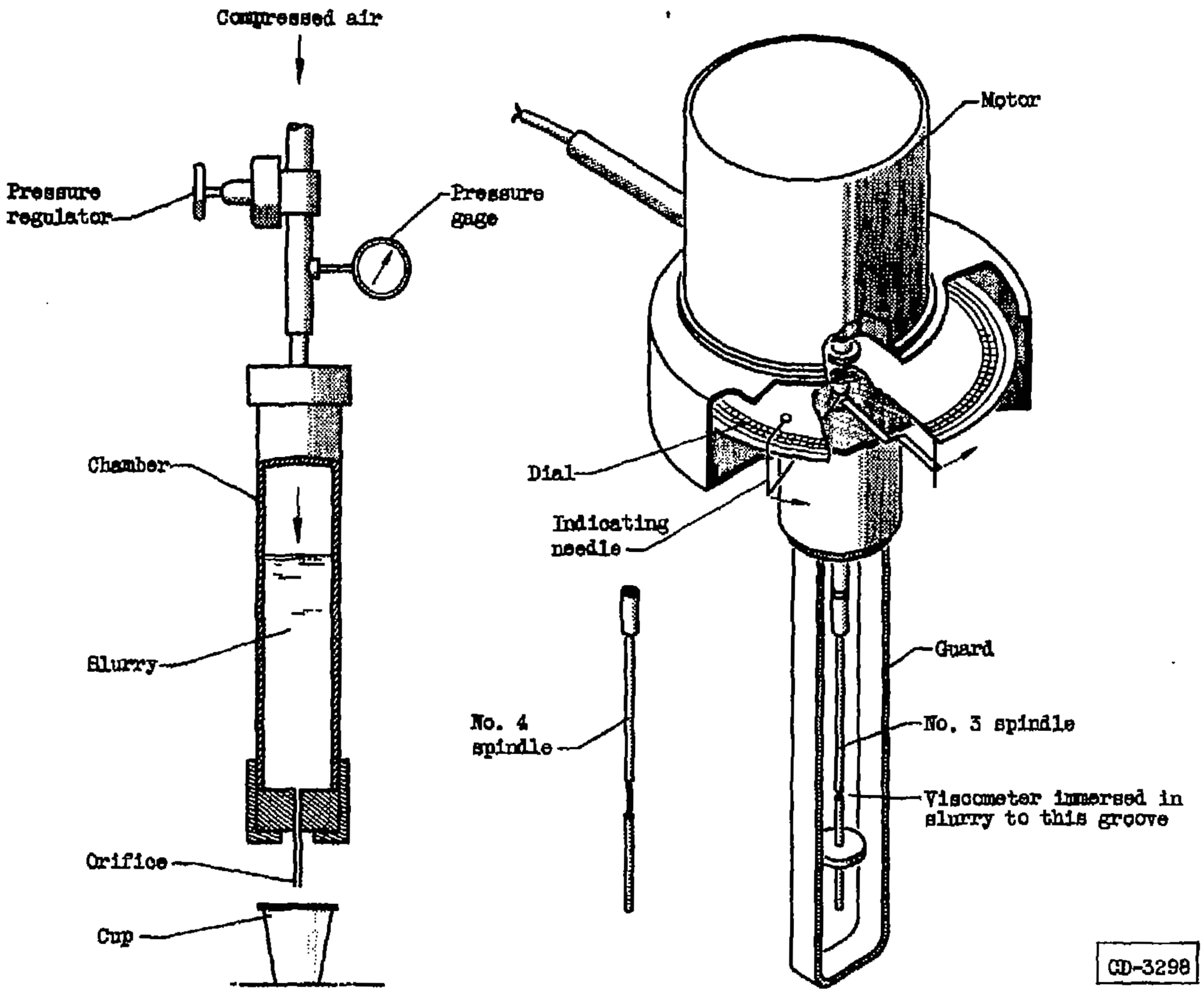
TABLE VIII. - Concluded. SUMMARY OF SEVERS EXTRUSION RHEOMETER DATA AND CALCULATED RATE OF SHEAR, SHEARING STRESS, AND APPARENT VISCOSITY OF MAGNESIUM - JP-4 SLURRIES STABILIZED WITH FIVE PETROLATUMS, OF PETROLATUM - JP-4 MIXTURES, AND OF GLYCEROL-WATER

Pressure, P, lb/sq in.	Weight of material extruded, M, g	Time required to extrude M grams, t, sec	Volume rate of extrusion, Q, cc/sec (a)	Rate of shear, σ, sec^{-1} (a)	Reciprocal of rate of shear, 1/σ, sec (a)	Shearing stress, $\frac{Pr}{2l}$, psi (a)	Apparent viscosity, η, centipoises
Magnesium, 55.0 percent; 45.0 percent medium consisting of 28 percent petrolatum E and 72 percent JP-4; density, 1.133 g/cc; temperature, 82° F							
2.3	38.4	89.62	0.3782	2,591	38.60×10^{-5}	0.01293	34.2
4.1	35.1	42.80	.7238	4,958	20.17	.02304	31.8
6.0	34.0	27.78	1.080	7,398	13.52	.03372	31.2
8.0	35.0	21.24	1.454	9,960	10.04	.04496	30.9
10.0	41.5	19.73	1.856	12,710	7.865	.05620	30.3
12.0	38.5	15.34	2.215	15,170	6.591	.06744	30.4
Magnesium, 60.0 percent; 40.0 percent medium consisting of 28 percent petrolatum E and 72 percent JP-4; density, 1.178 g/cc; temperature, 82° F							
2.2	28.7	99.31	0.2453	1,680	59.52×10^{-5}	0.01236	50.4
4.1	25.3	41.97	.5117	3,505	28.53	.02304	45.0
6.0	30.1	32.52	.7857	5,382	18.58	.03372	42.9
8.0	26.5	24.30	.9258	6,342	15.77	.04496	48.6
10.0	28.4	20.12	1.198	8,206	12.19	.05620	46.9
12.0	28.8	18.18	1.345	9,213	10.85	.06744	50.1
Magnesium, 65.0 percent; 35.0 percent medium consisting of 28 percent petrolatum E and 72 percent JP-4; density, 1.228 g/cc; temperature, 81° F							
2.2	19.7	166.9	0.09612	658.4	151.9×10^{-5}	0.01236	129
4.1	20.0	70.51	.2310	1,582	63.21	.02304	99.8
6.1	21.3	47.16	.3678	2,519	39.70	.03428	93.2
8.0	24.4	37.83	.5252	3,598	27.79	.04496	85.6
10.0	20.7	25.87	.6516	4,463	22.41	.05620	86.3
Magnesium, 0 percent; petrolatum B, 44.4 percent; JP-4, 55.6 percent; density, 0.808 g/cc; temperature, 81° F							
0.24	14.2	102.1	0.1721	1,179	84.82×10^{-5}	0.001349	7.84
2.3	13.5	9.77	1.710	11,710	8.537	.01293	7.56
3.2	13.3	6.91	2.382	16,320	6.128	.01798	7.55
4.1	14.6	6.09	2.967	20,320	4.920	.02304	7.77
5.0	16.4	5.69	3.567	24,430	4.093	.02810	7.88
7.1	18.0	4.86	4.584	31,400	3.185	.03990	8.70
Magnesium, 0 percent; petrolatum B, 52.0 percent; JP-4, 48.0 percent; density, 0.816 g/cc; temperature, 81° F							
1.2	23.3	73.10	0.3906	2,676	37.37×10^{-5}	0.006744	17.3
3.2	24.4	28.44	1.051	7,199	13.89	.01798	17.1
5.0	25.6	15.98	1.963	13,450	7.437	.02810	14.3
7.0	27.5	12.21	2.760	18,910	5.289	.03934	14.2
9.0	25.5	8.90	3.511	24,050	4.158	.05058	14.4
Magnesium, 0 percent; petrolatum B, 60.0 percent; JP-4, 40.0 percent; density, 0.823 g/cc; temperature, 79° F							
2.2	22.2	114.6	0.2354	1,612	62.03×10^{-5}	0.01236	52.5
4.1	24.2	62.15	.4731	3,241	30.85	.02304	48.7
6.0	26.9	37.02	.8829	6,048	16.53	.03372	38.2
8.0	26.7	24.10	1.346	9,220	10.85	.04496	33.4
10.0	27.0	18.21	1.802	12,340	8.101	.05620	31.2
C.P. glycerol (glycerol, 95 percent; water, 5 percent); density, 1.248 g/cc; temperature, 86° F							
2.4	17.7	257.6	0.05506	377.2	265.1×10^{-5}	0.01349	245
4.3	19.3	155.8	.09926	679.9	147.1	.02417	244
7.2	20.2	96.28	.1681	1,151	86.88	.04046	241
10.0	20.6	70.14	.2353	1,612	62.03	.05620	239
14.0	23.5	58.11	.3240	2,219	45.07	.07868	243
18.0	23.8	46.18	.4130	2,829	35.35	.1012	245

[a]Only three figures are significant, although more are shown to facilitate calculation.



Severs Extrusion Rheometer

Brookfield Synchro-lectric Viscometer

Figure 1. - Viscometers used to study magnesium-hydrocarbon slurries and their media.

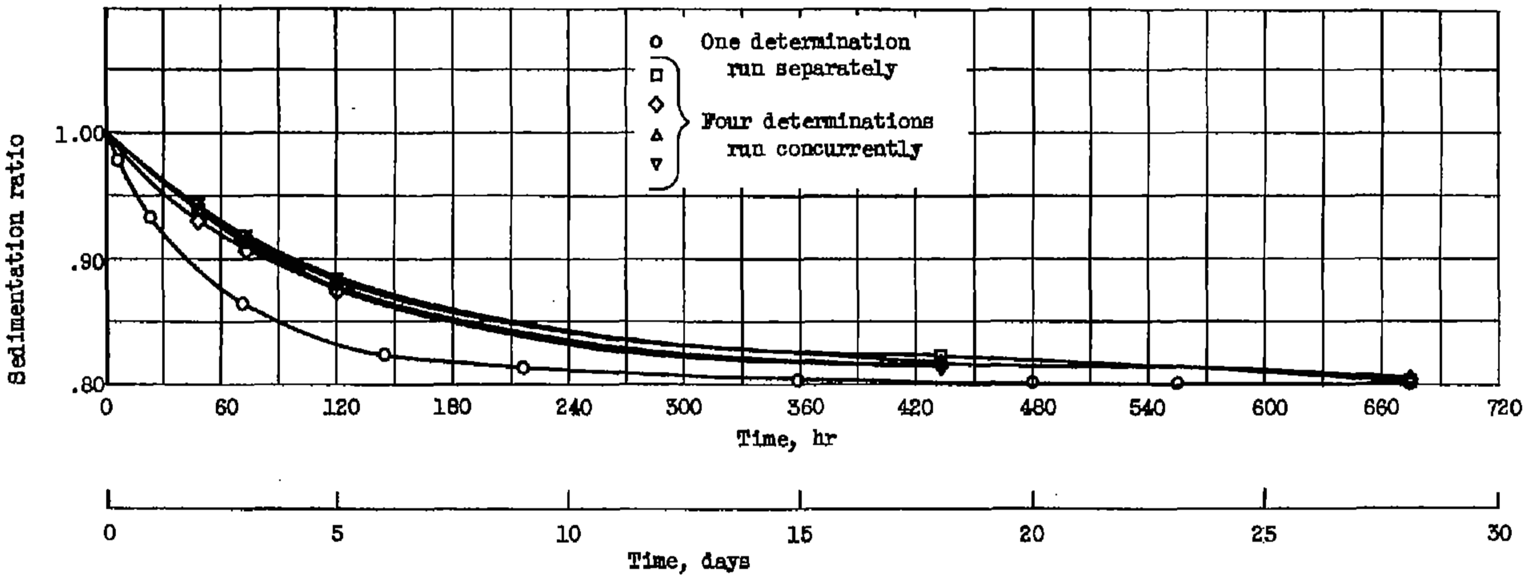


Figure 2. - Reproducibility of sedimentation ratio - time curve for 50-percent magnesium slurry stabilized with petrolatum. Temperature, 86° F; slurry composition: 50 percent magnesium powder; 14 percent petrolatum E; 36 percent MIL-F-5624A, grade JP-4 fuel.

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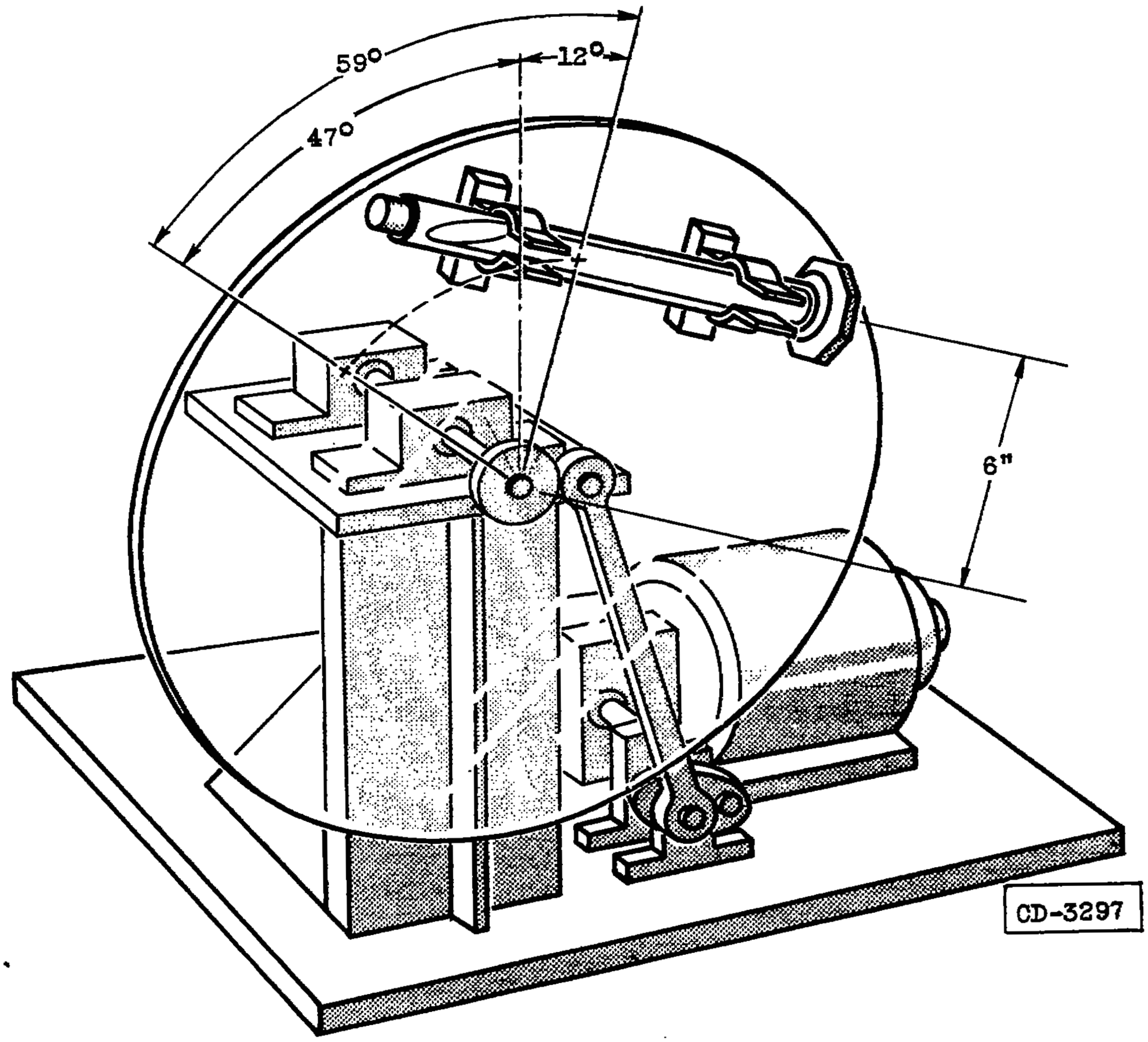

Figure 3. - Shaker used in determination of redispersibility.

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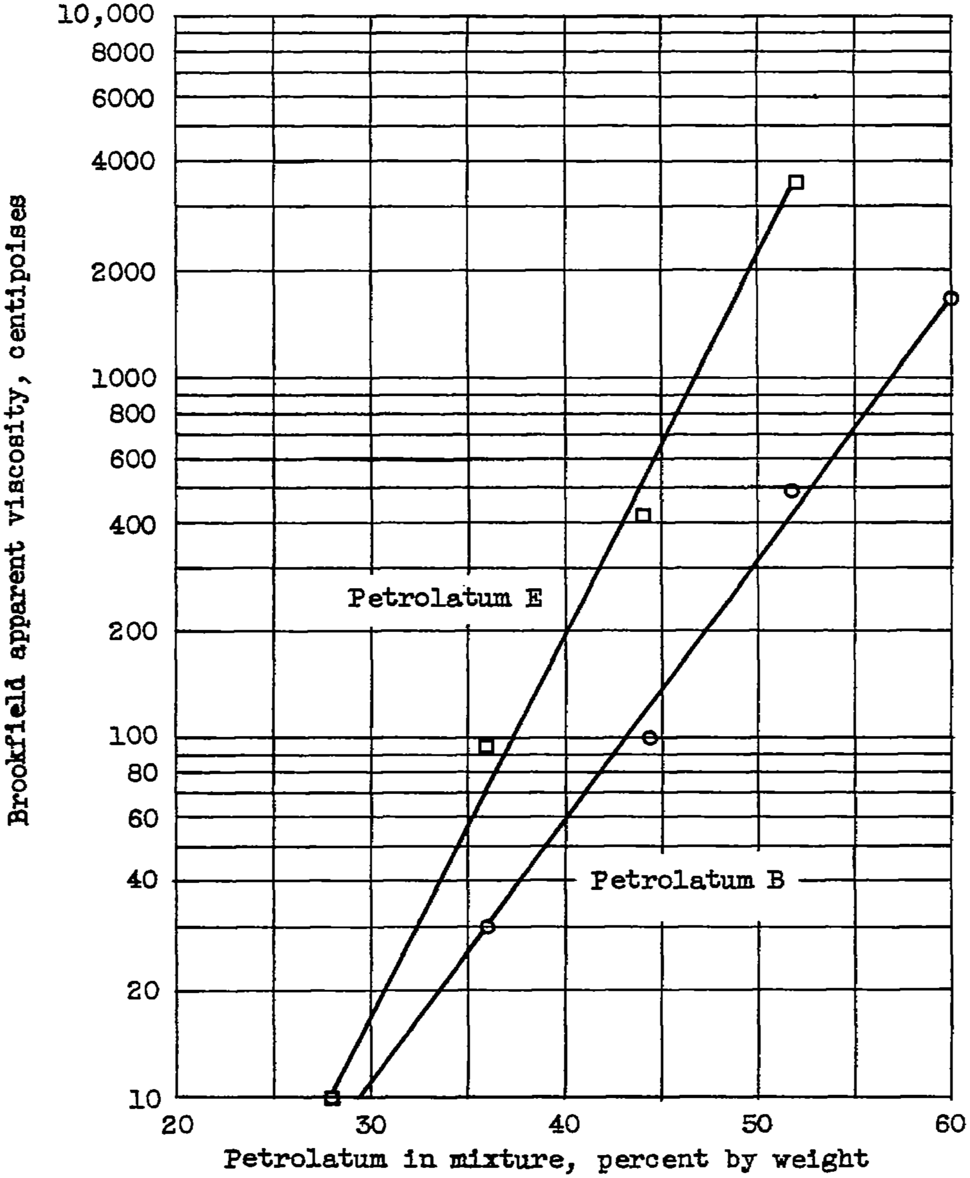

Figure 4. - Effect of petrolatum concentration on Brookfield apparent viscosity of mixtures of each of two petrolatums with MIL-F-5624A, grade JP-4 fuel. Temperature, 86° F.

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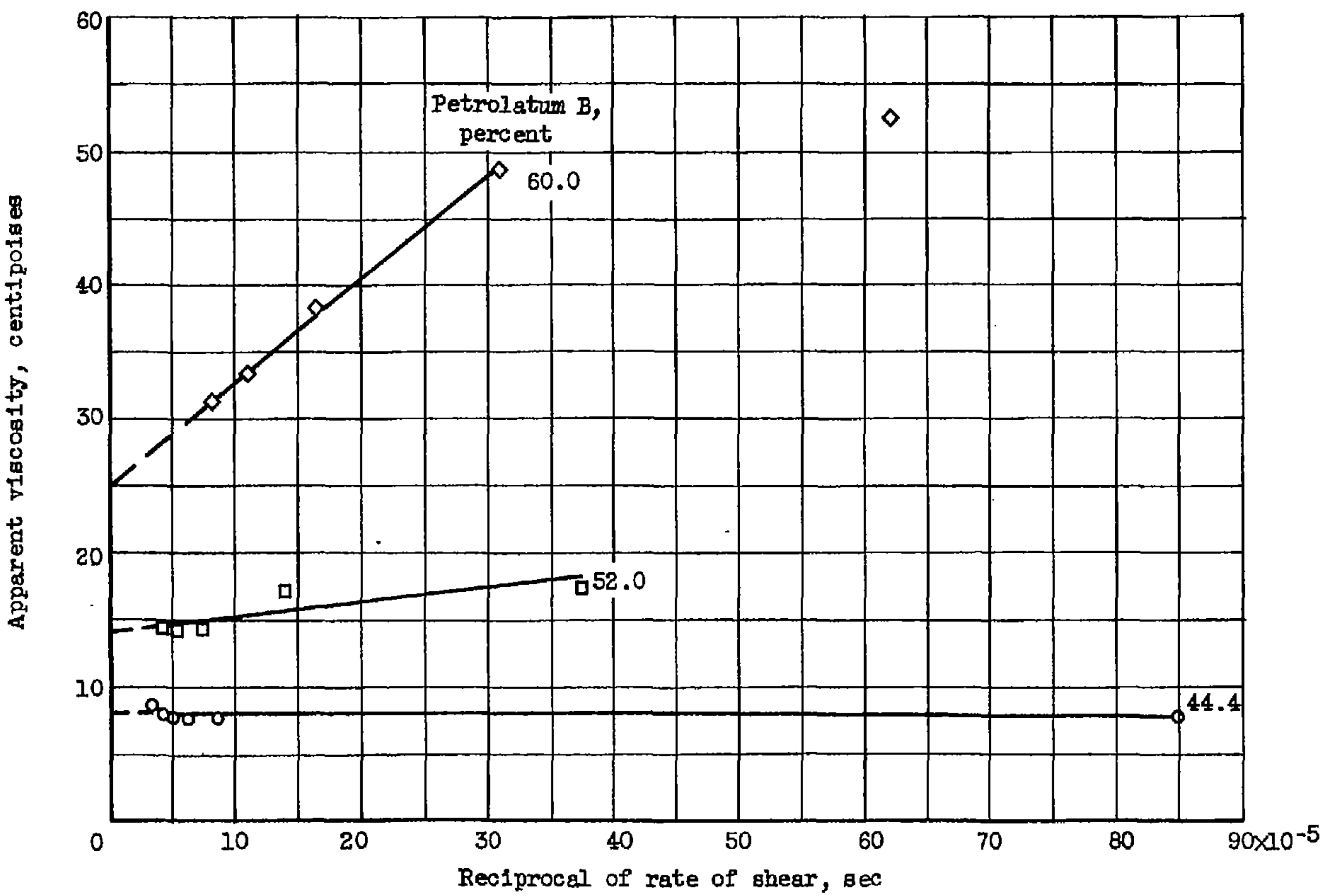

Figure 5. - Change of apparent viscosity with reciprocal of rate of shear for mixtures of petrolatum B and MIL-F-5624A, grade JP-4. Measurements made with Severs Extrusion Rheometer; temperature, 79° to 81° F.

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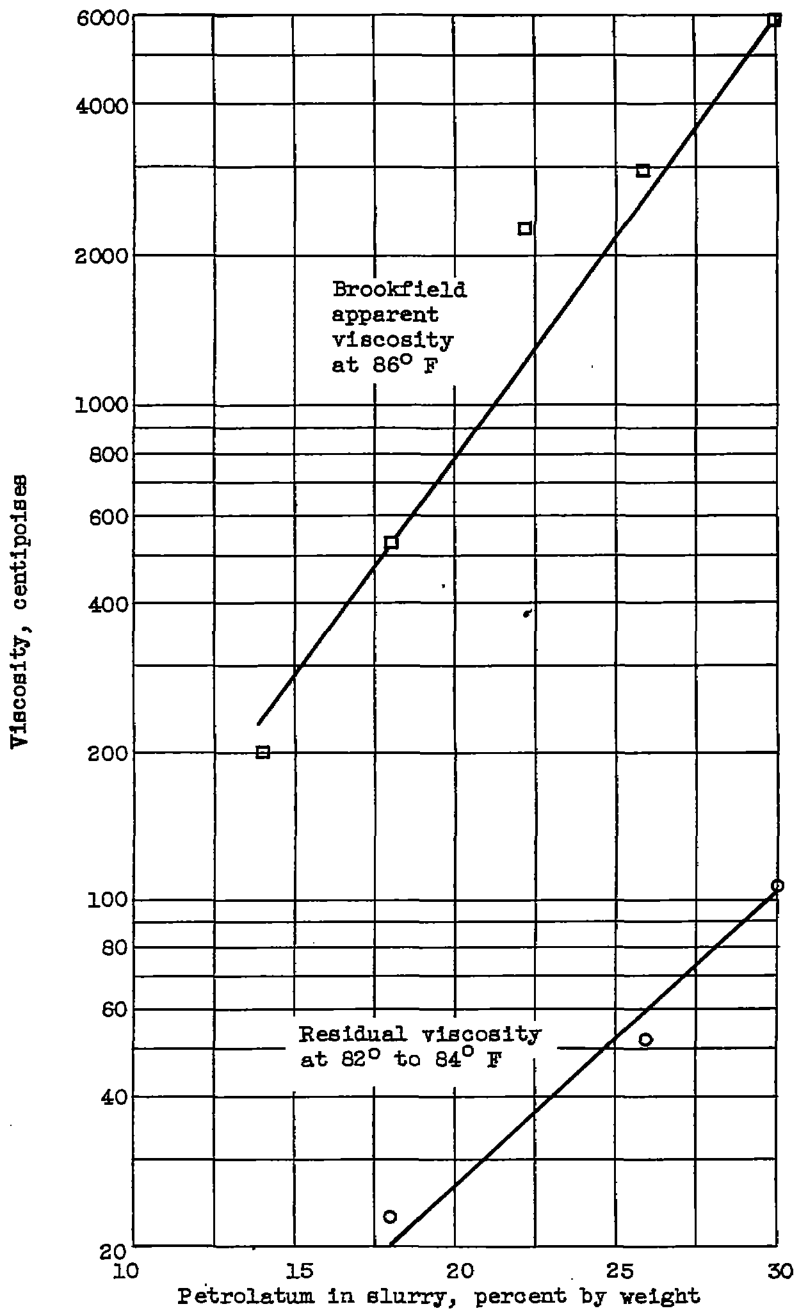

(a) Hydrocarbon medium composed of petrolatum A and MIL-F-5624A, grade JP-4.

Figure 6. - Effect of petrolatum concentration on residual and Brookfield apparent viscosities of 50-percent magnesium slurries stabilized with petrolatum.

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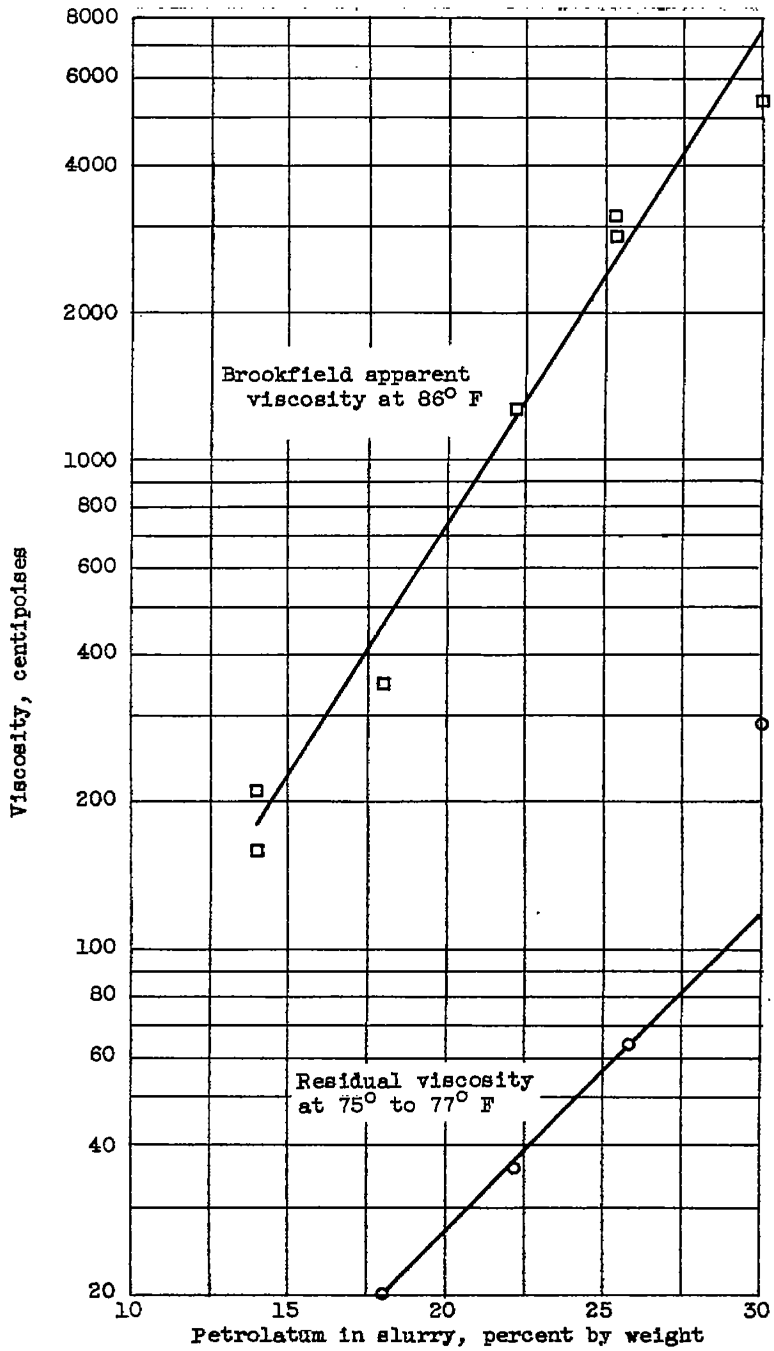

(b) Hydrocarbon medium composed of petrolatum B and MIL-F-5624A, grade JP-4.

Figure 6. - Continued. Effect of petrolatum concentration on residual and Brookfield apparent viscosities of 50-percent magnesium slurries stabilized with petrolatum.

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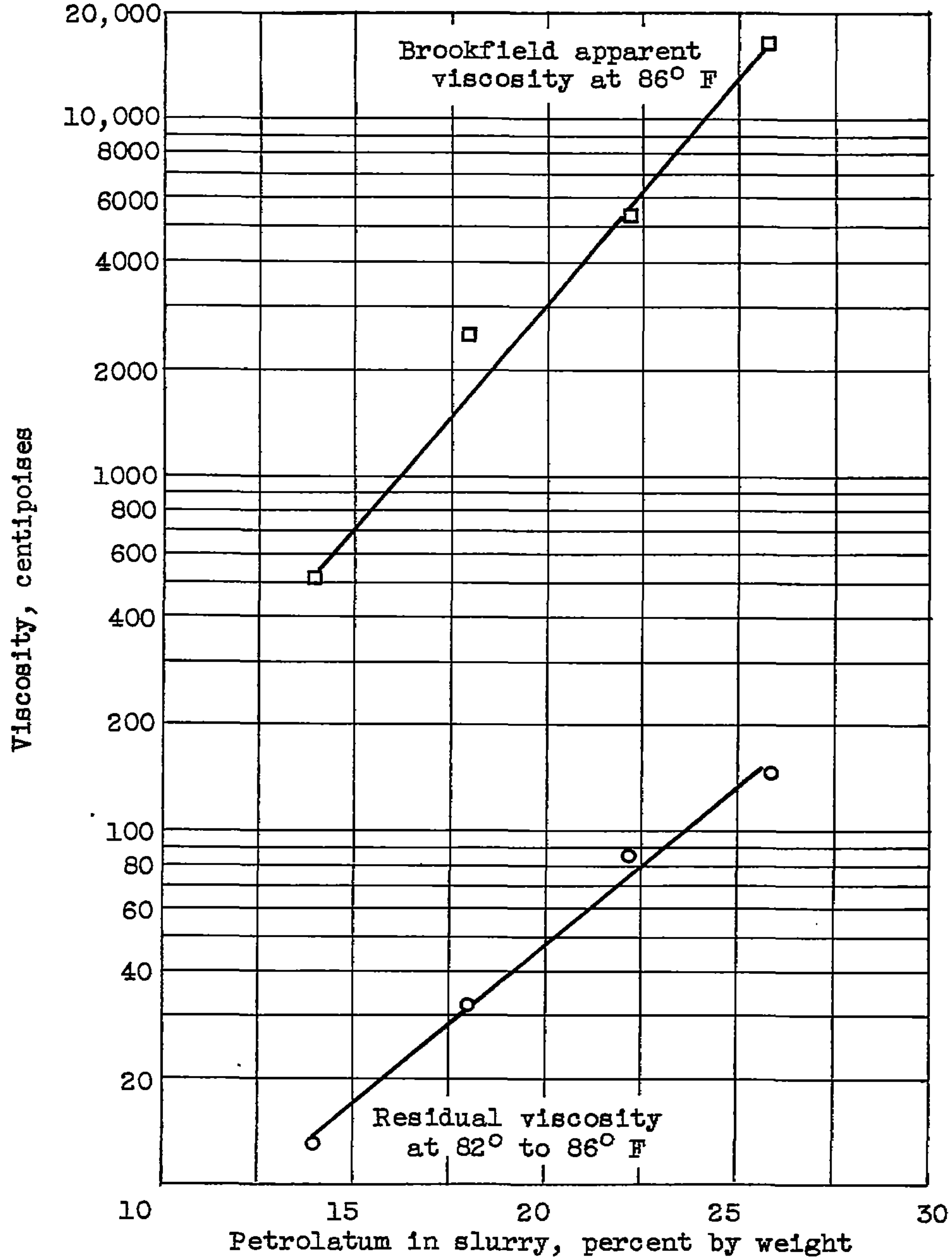

(c) Hydrocarbon medium composed of petrolatum C and MIL-F-5624A, grade JP-4.

Figure 6. - Continued. Effect of petrolatum concentration on residual and Brookfield apparent viscosities of 50-percent magnesium slurries stabilized with petrolatum.

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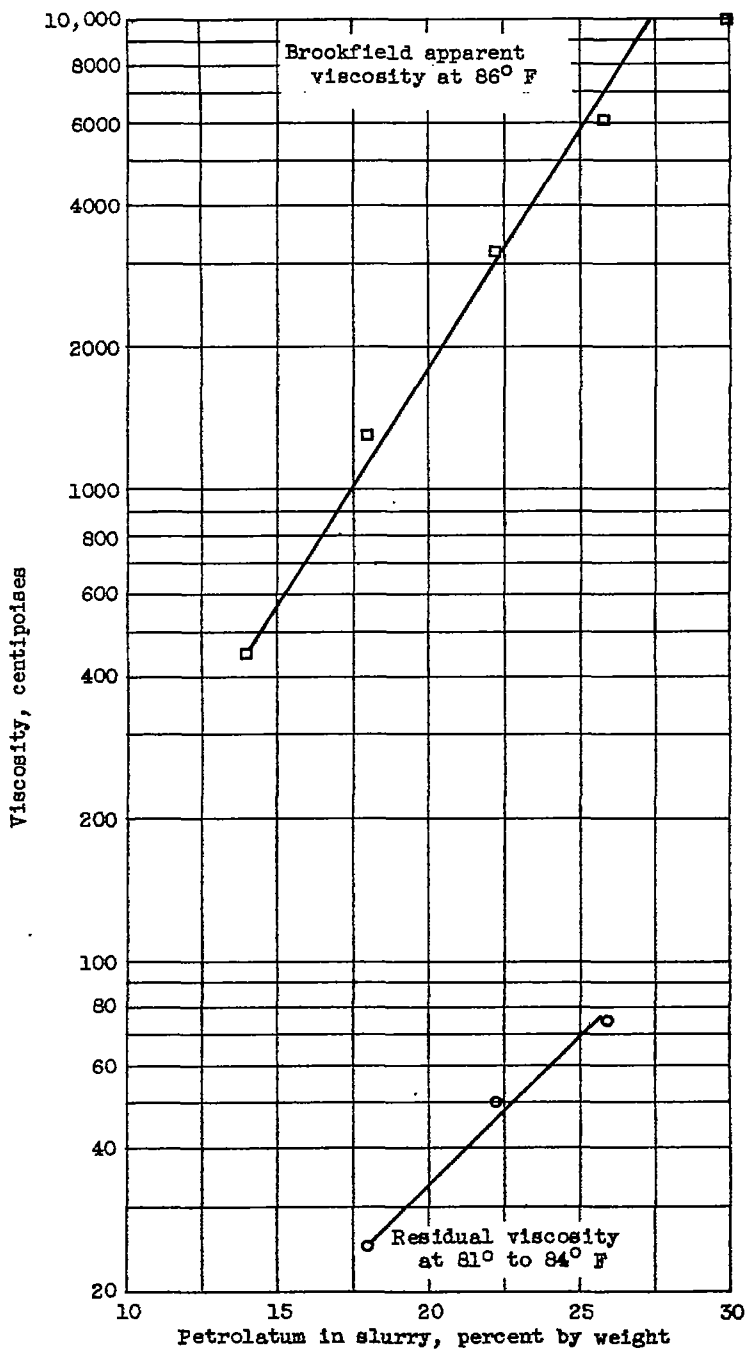

(d) Hydrocarbon medium composed of petrolatum D and MIL-F-5624A, grade JP-4.

Figure 6. - Continued. Effect of petrolatum concentration on residual and Brookfield apparent viscosities of 50-percent magnesium slurries stabilized with petrolatum.

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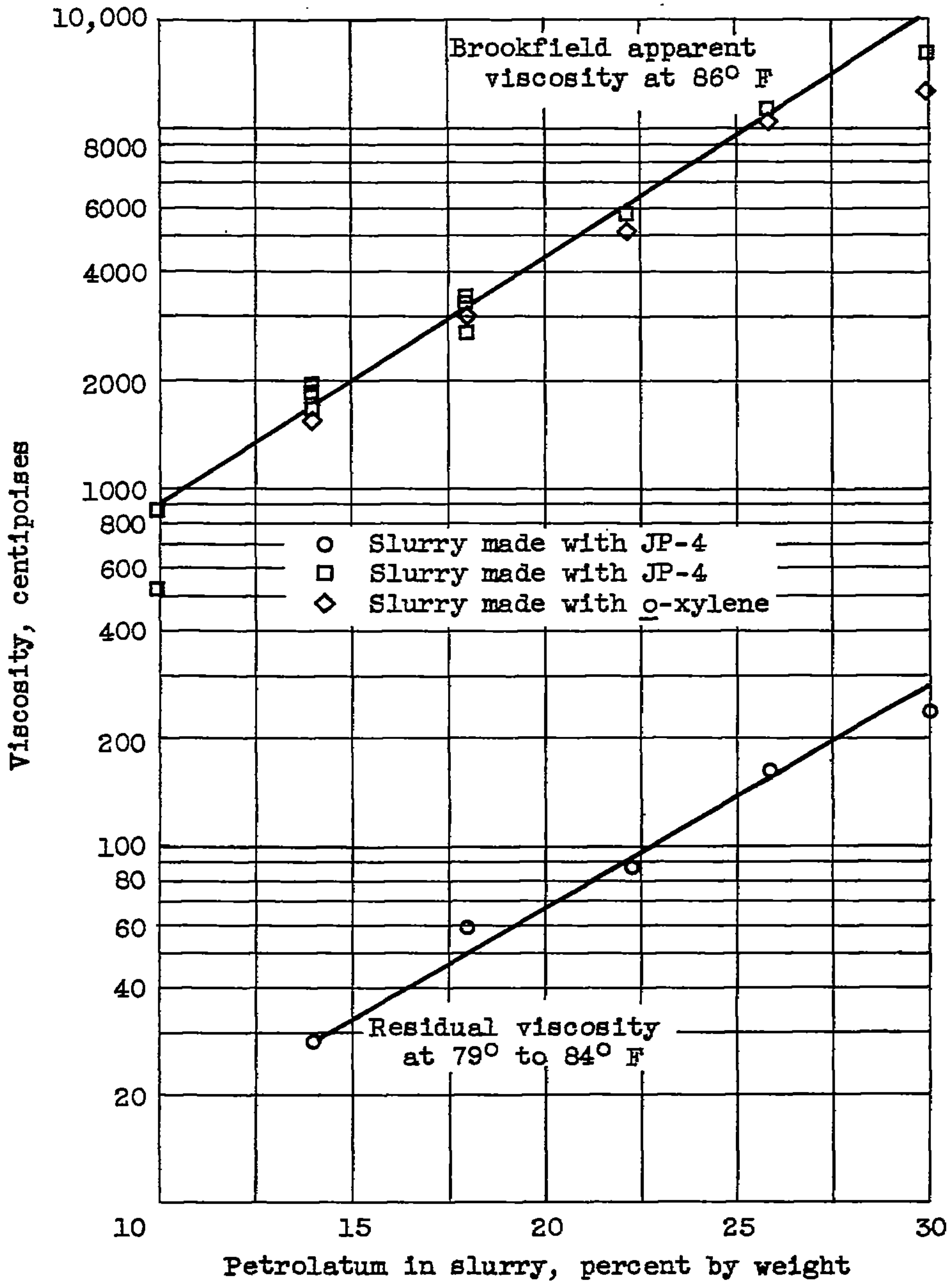

(e) Hydrocarbon medium composed of petrolatum E and either MIL-F-5624A, grade JP-4 or o-xylene.

Figure 6. - Concluded. Effect of petrolatum concentration on residual and Brookfield apparent viscosities of 50-percent magnesium slurries stabilized with petrolatum.

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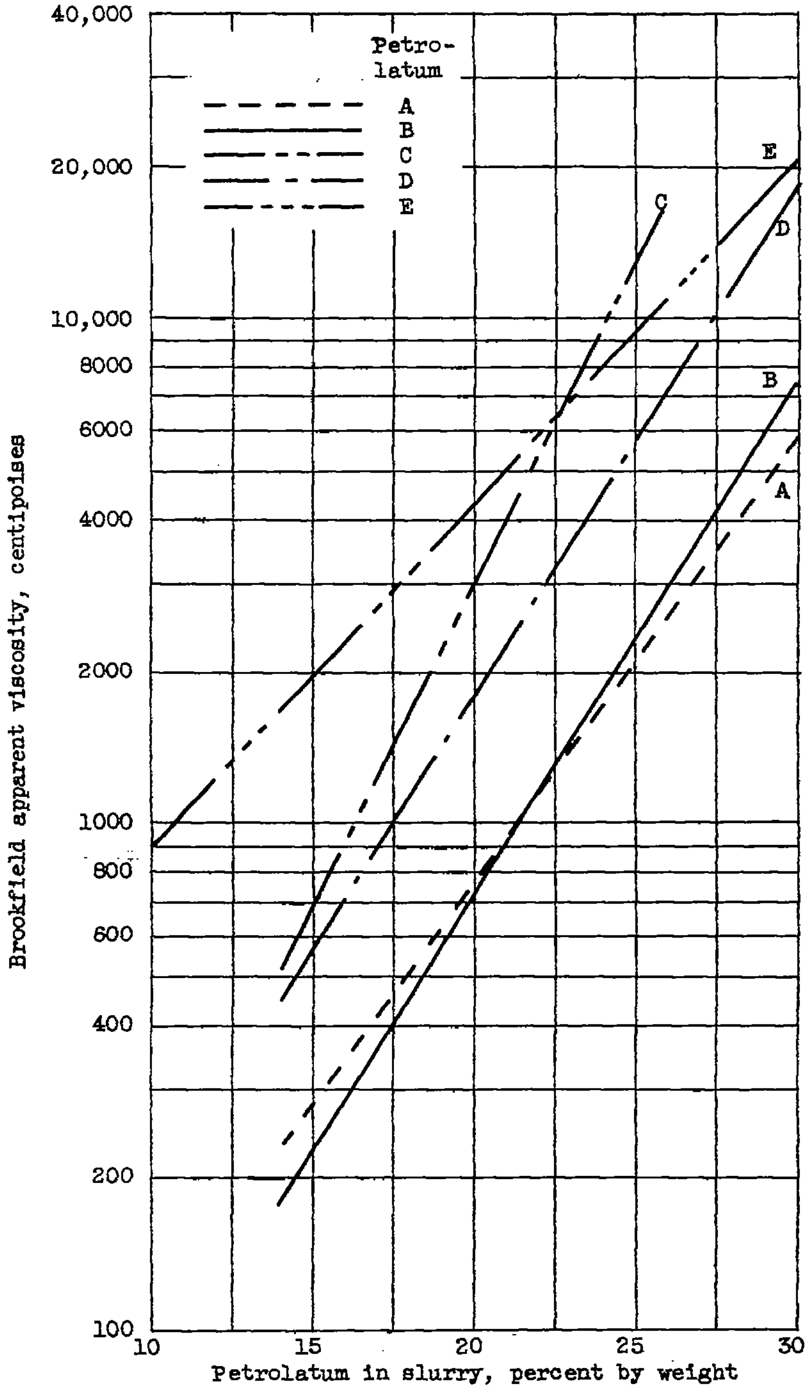

Figure 7. - Summary of effect of petrolatum concentration on Brookfield apparent viscosity of 50-percent magnesium slurries. Temperature, 86° F; hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.

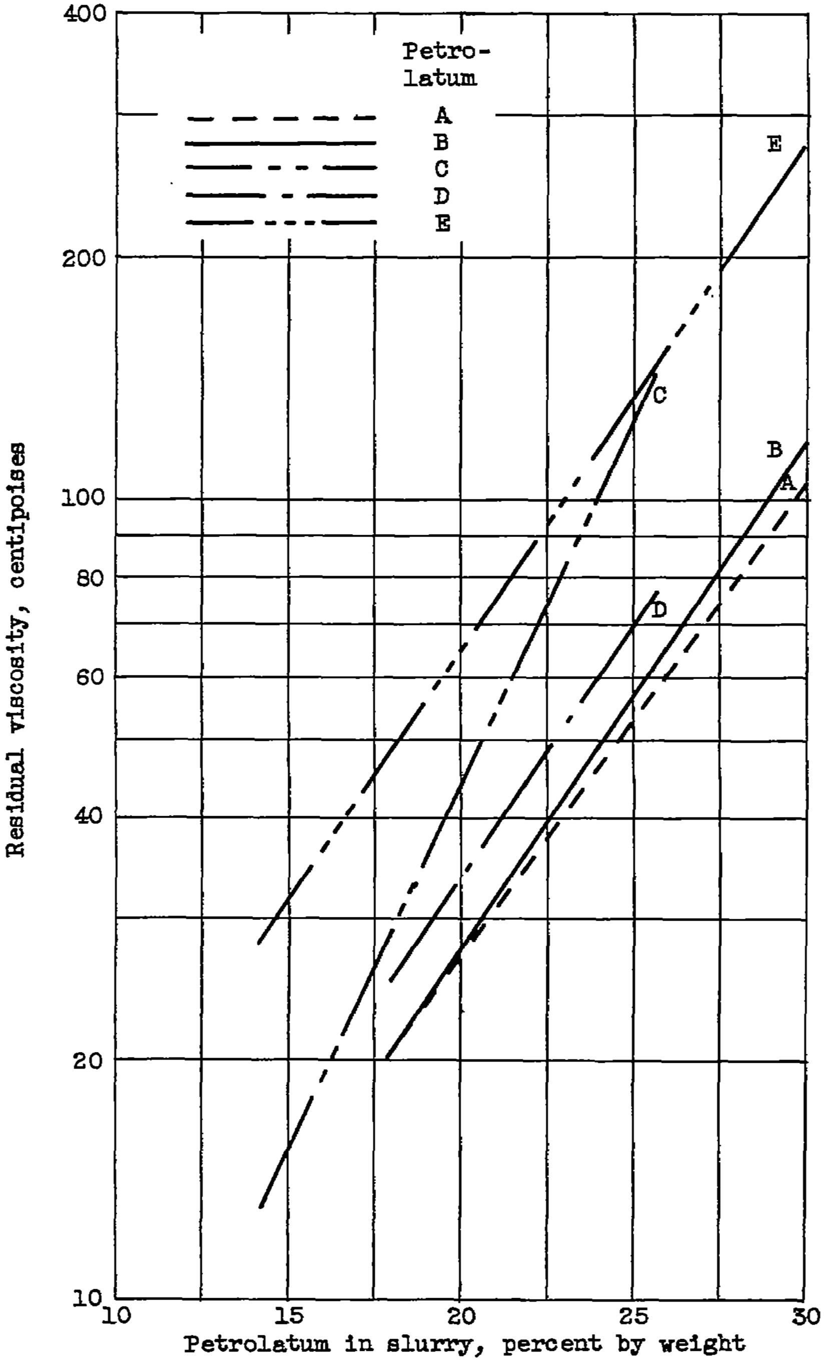

Figure 8. - Summary of effect of petrolatum concentration on residual viscosity of 50-percent magnesium slurries. Temperature, 75° to 86° F; hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.

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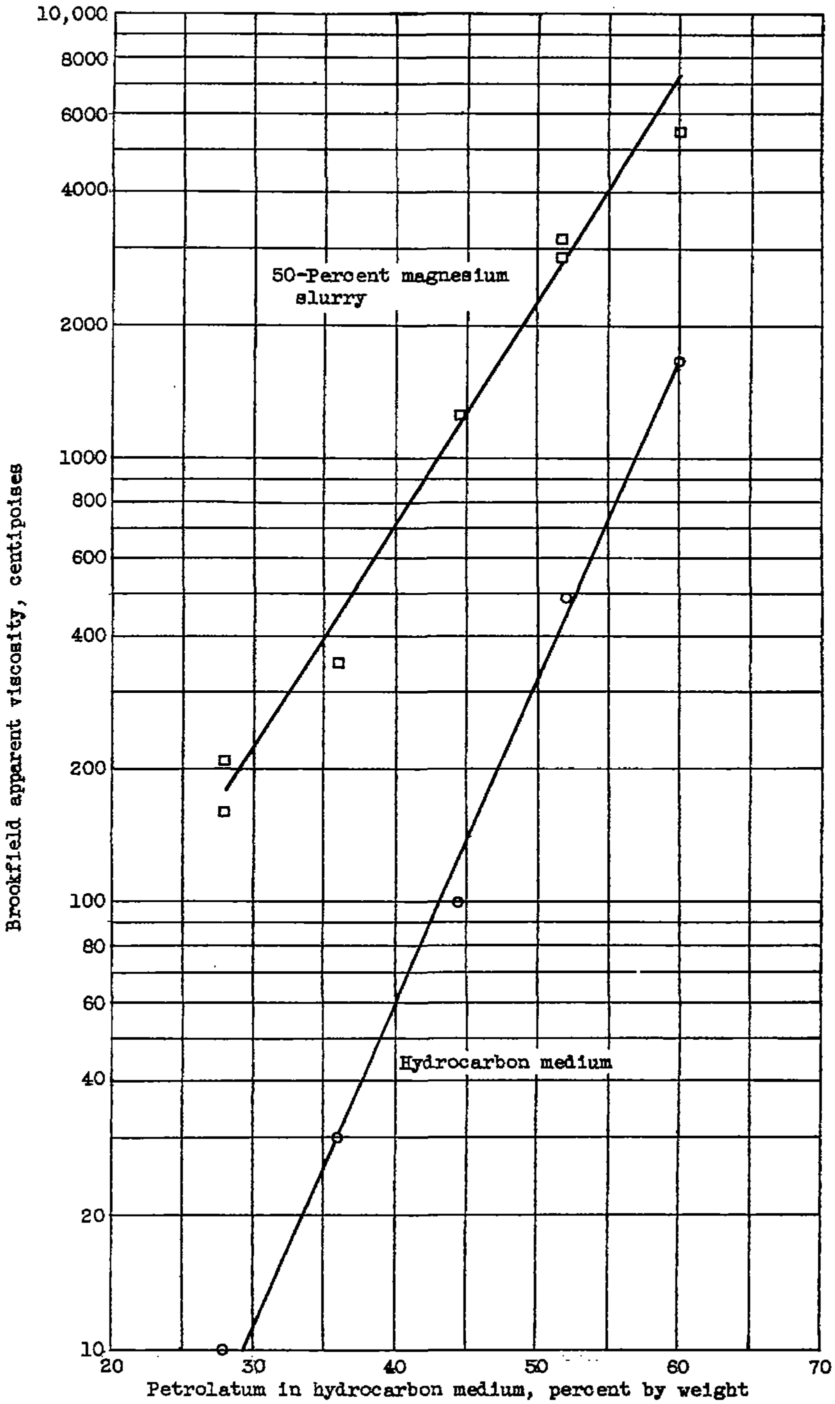

Figure 9. - Comparison between the Brookfield apparent viscosity of 50-percent magnesium slurries and that of their hydrocarbon media. Temperature, 86° F; media composed of petrolatum B and MIL-F-5624A, grade JP-4 fuel.

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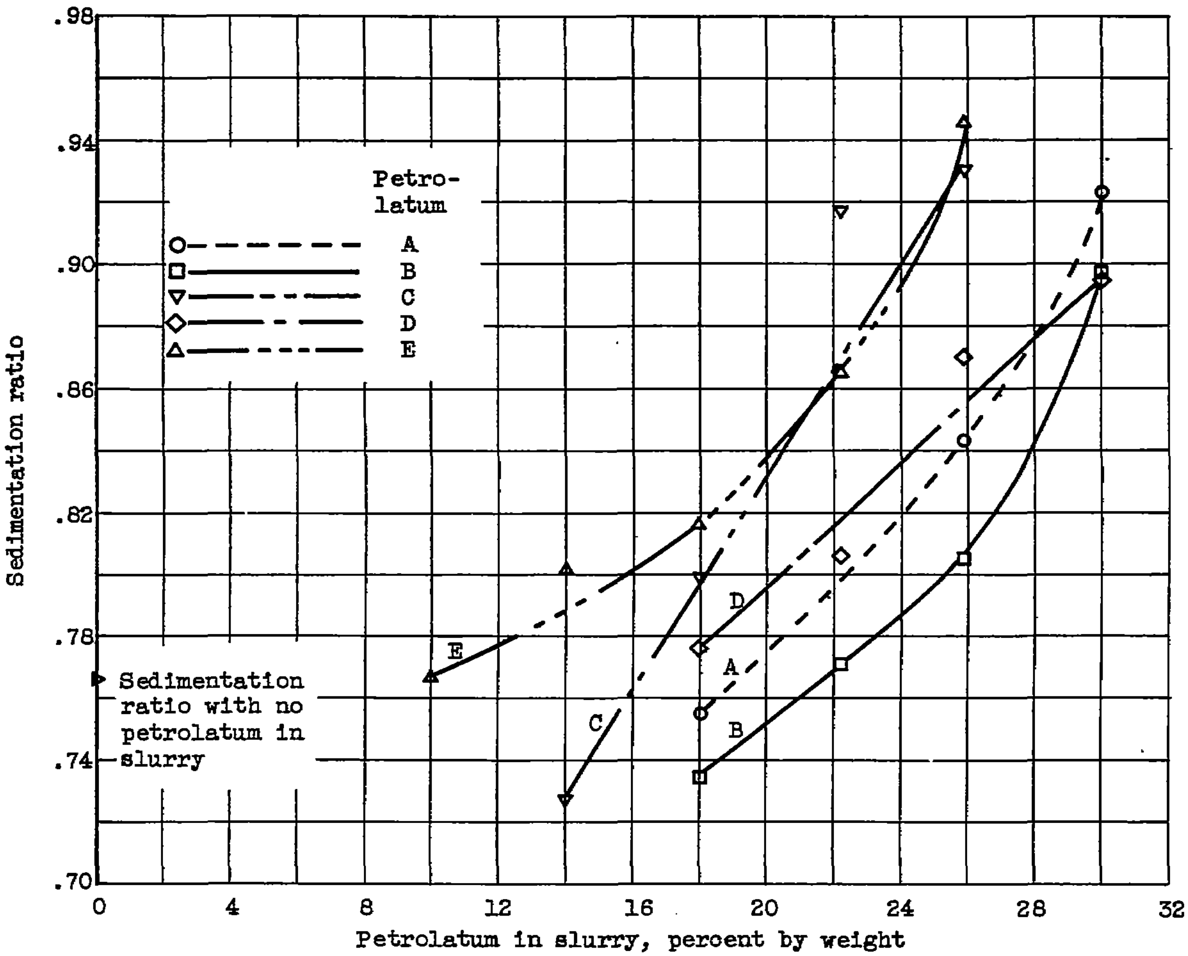

Figure 10. - Effect of petrolatum concentration on sedimentation ratio (after 28 days settling) of 50-percent magnesium slurries stabilized with each of five petrolatums. Temperature, 86° F; hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.

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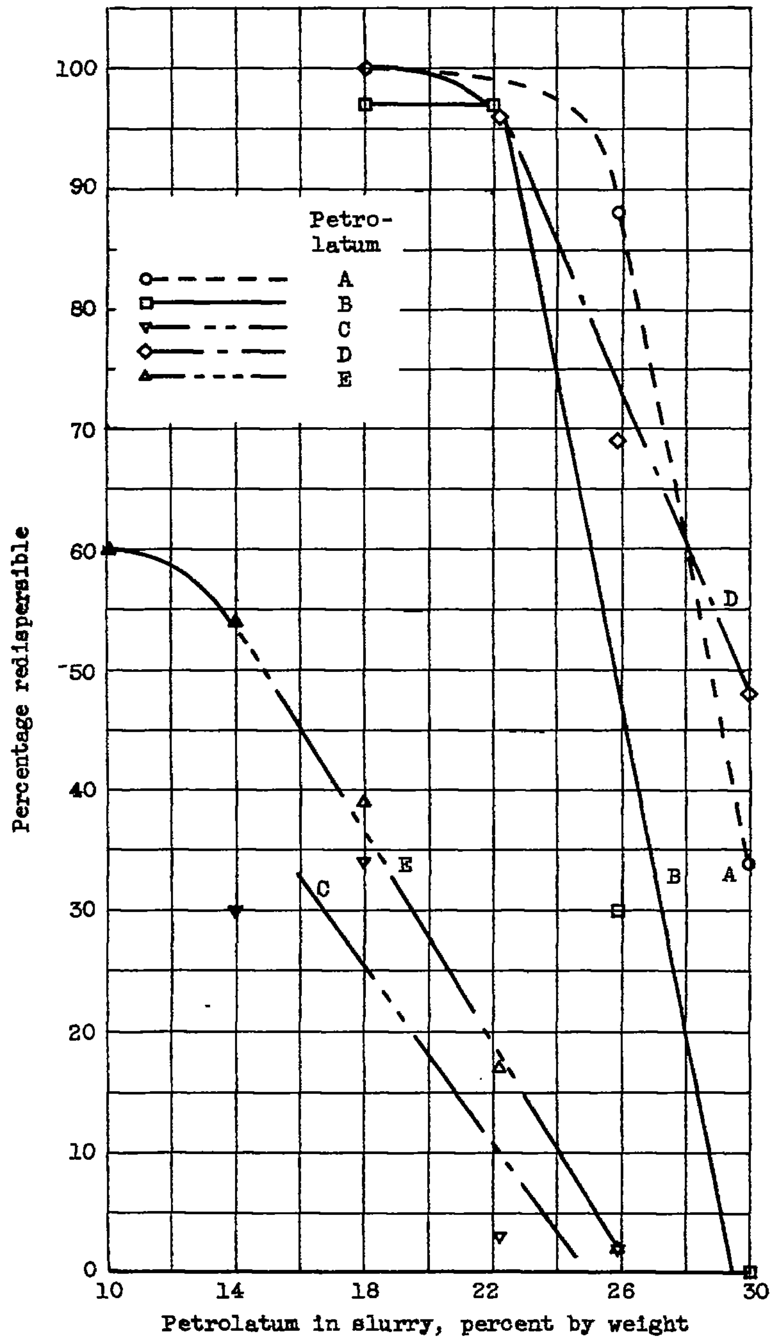

Figure 11. - Effect of petrolatum concentration on redispersibility of 50-percent magnesium slurries stabilized with each of five petrolatums. Hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.

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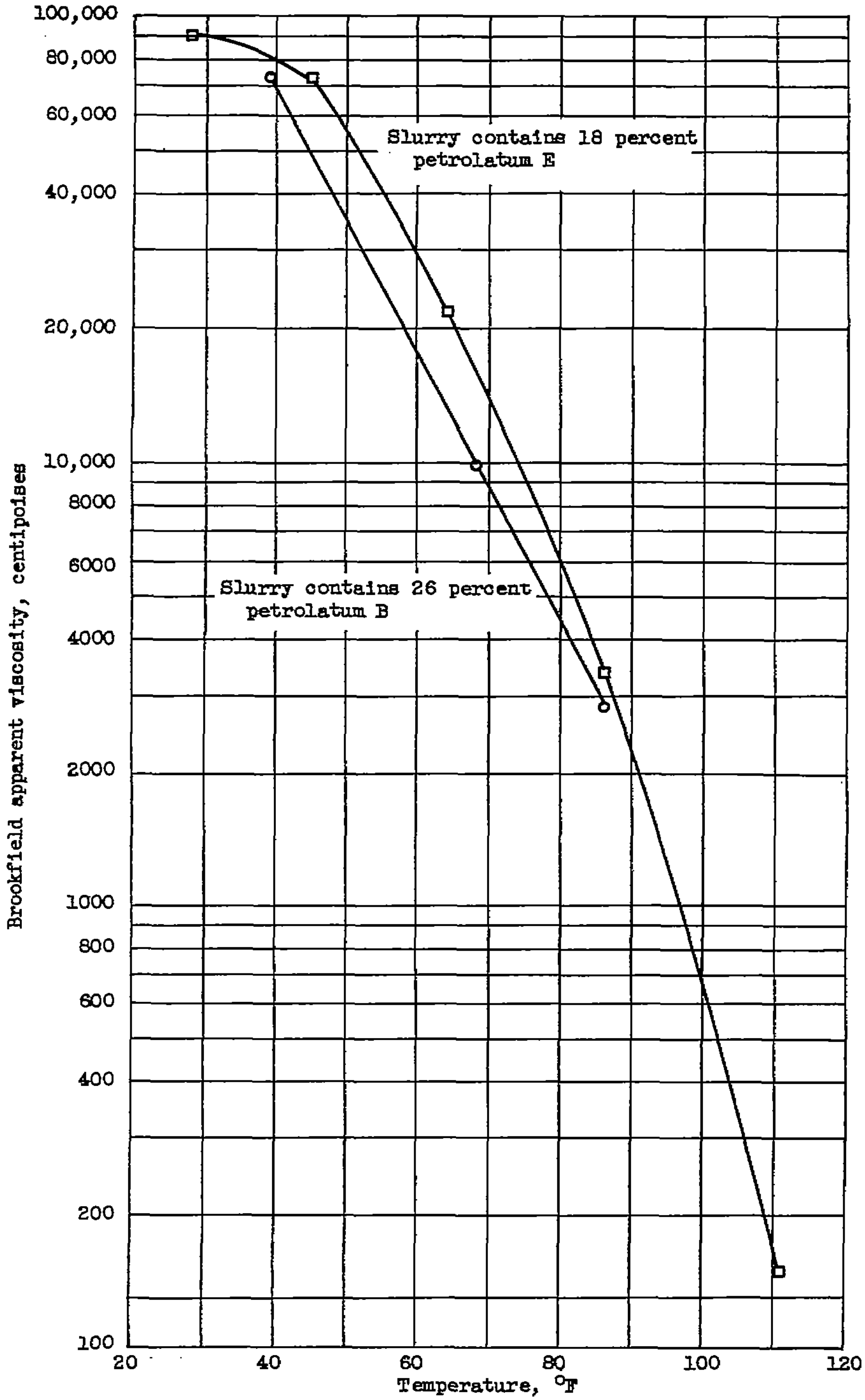

Figure 12. - Effect of temperature on Brookfield apparent viscosity of 50-percent magnesium slurries stabilized with petrolatum. Hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.

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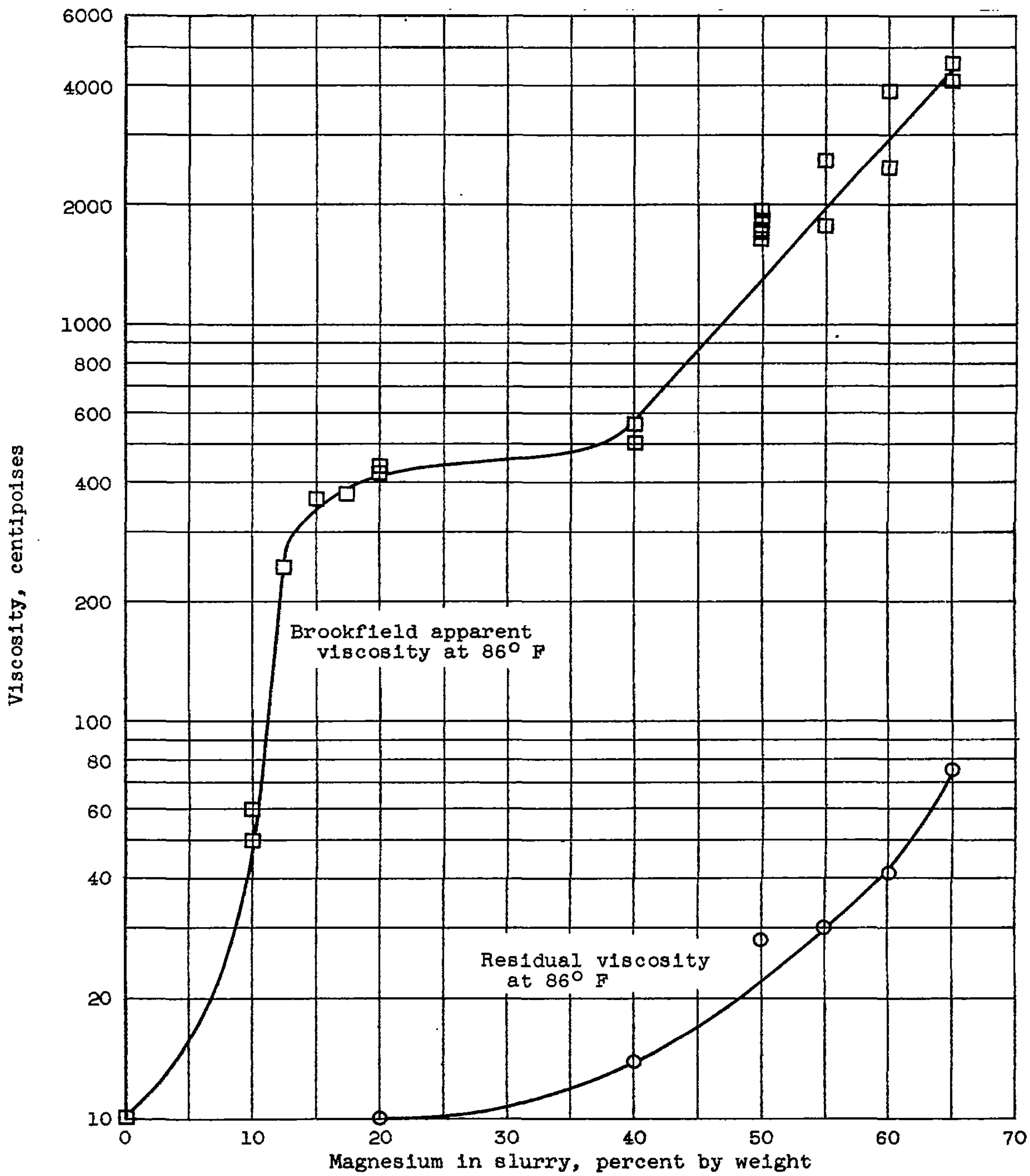

(a) Residual and Brookfield apparent viscosities.

Figure 13. - Effect of magnesium concentration on physical properties of magnesium slurries stabilized with petrolatum. Hydrocarbon medium composed of 28 percent petrolatum E and 72 percent MIL-F-5624A, grade JP-4 fuel.

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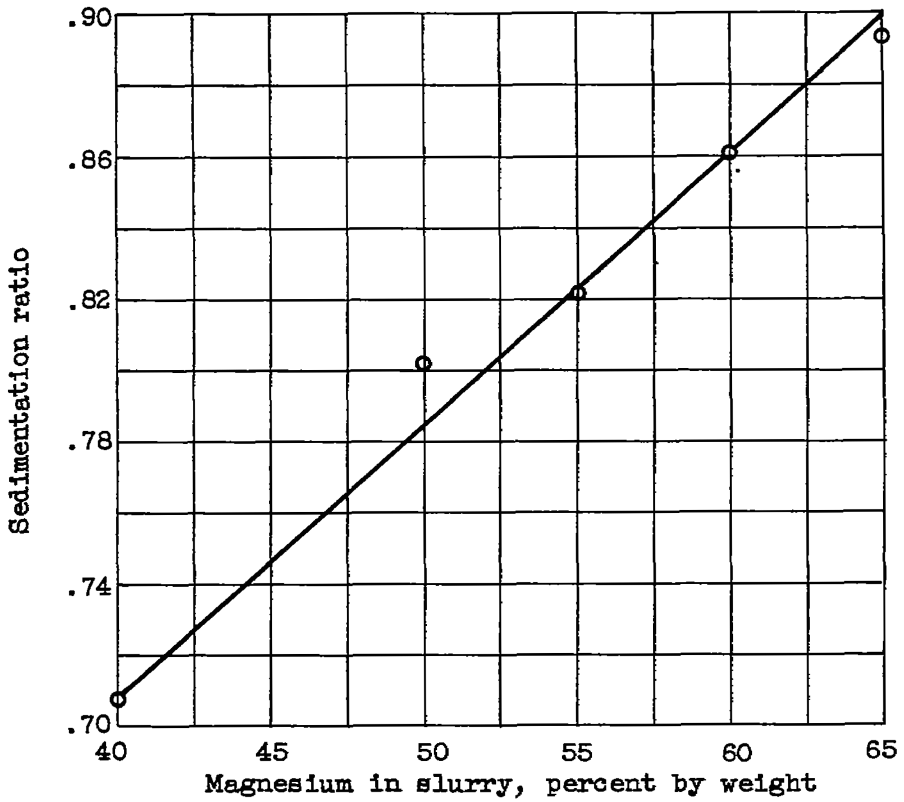

(b) Sedimentation ratio at 86° F.

Figure 13. - Continued. Effect of magnesium concentration on physical properties of magnesium slurries stabilized with petrolatum. Hydrocarbon medium composed of 28 percent petrolatum E and 72 percent MIL-F-5624A, grade JP-4 fuel.

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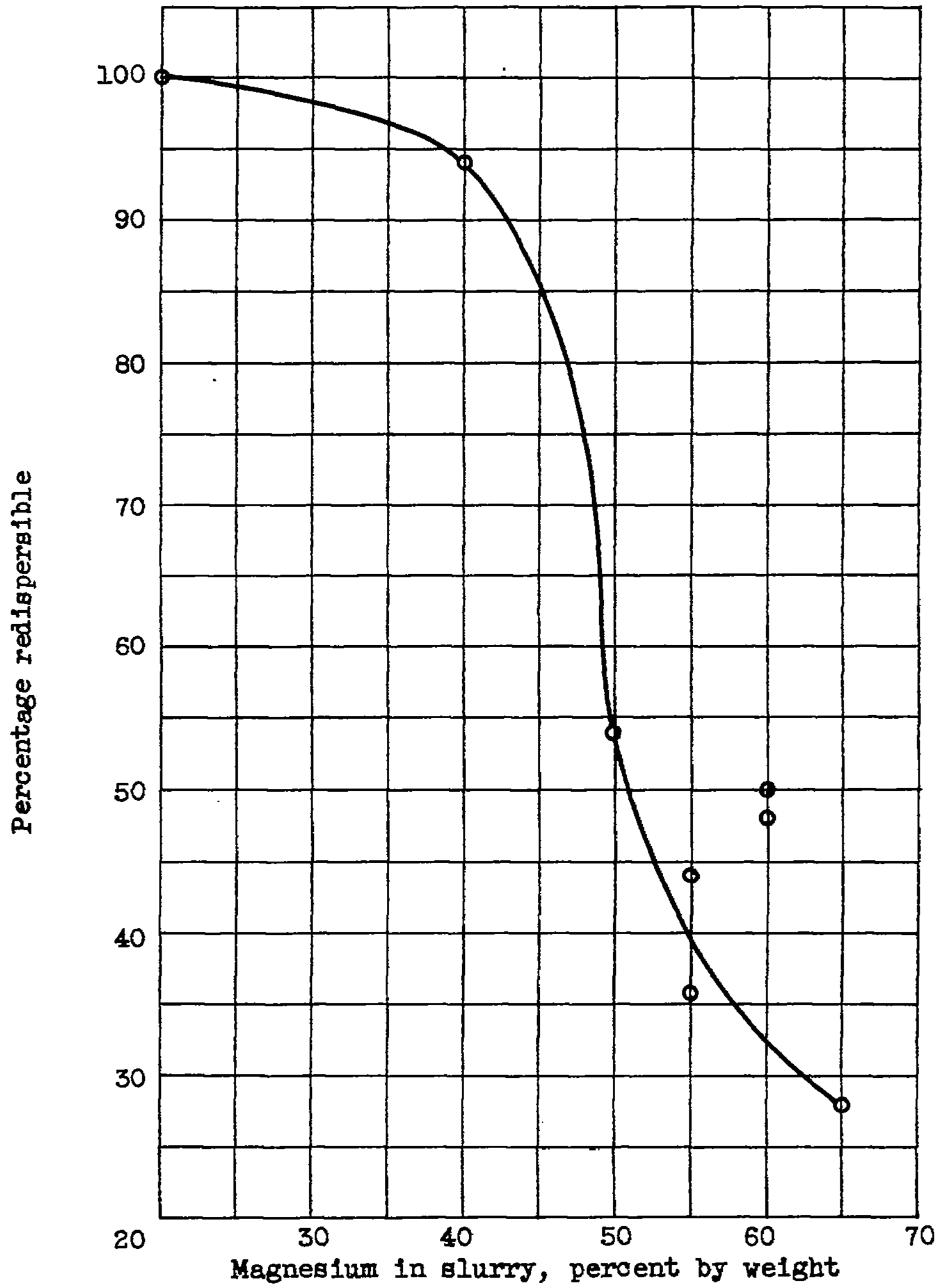
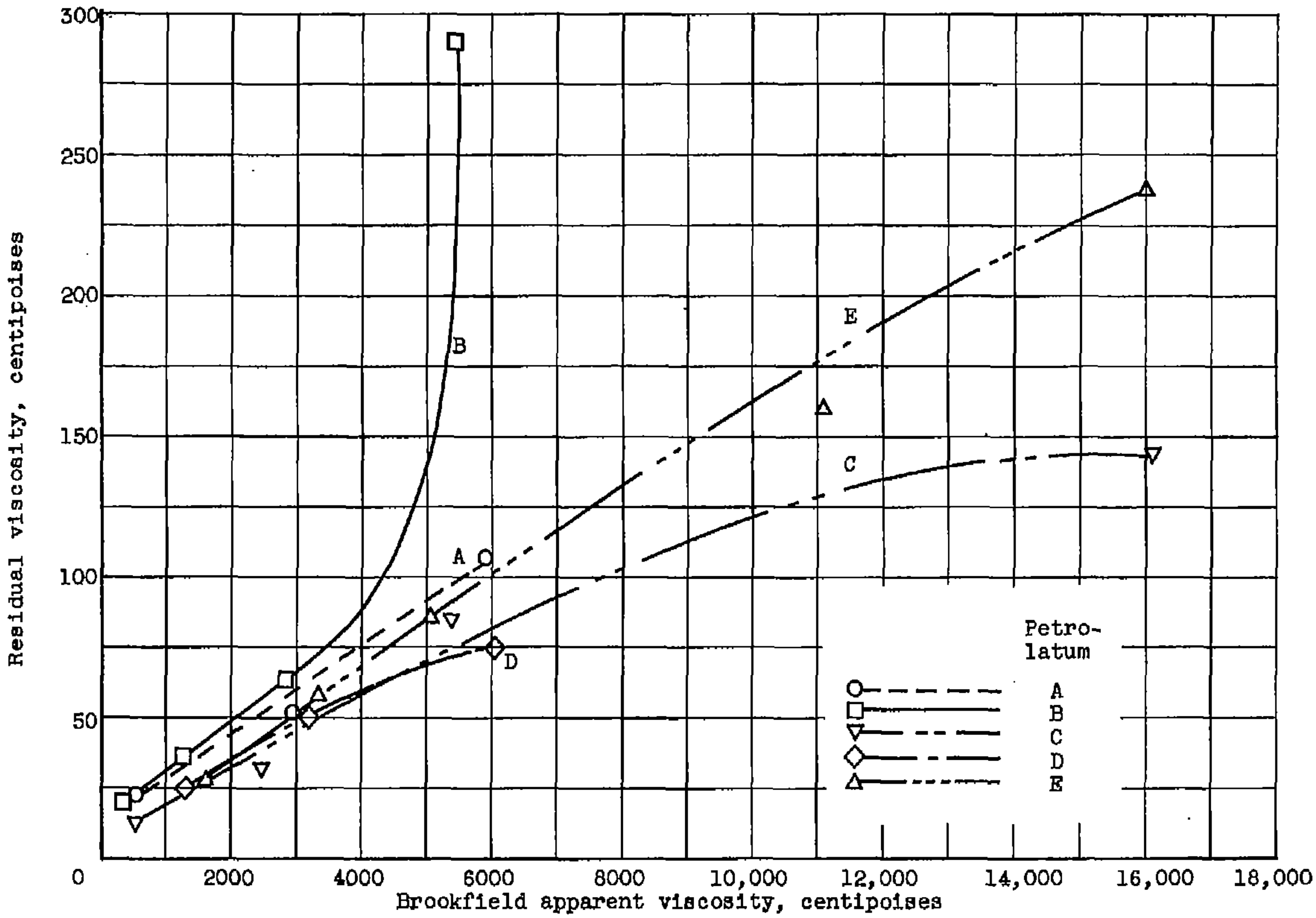


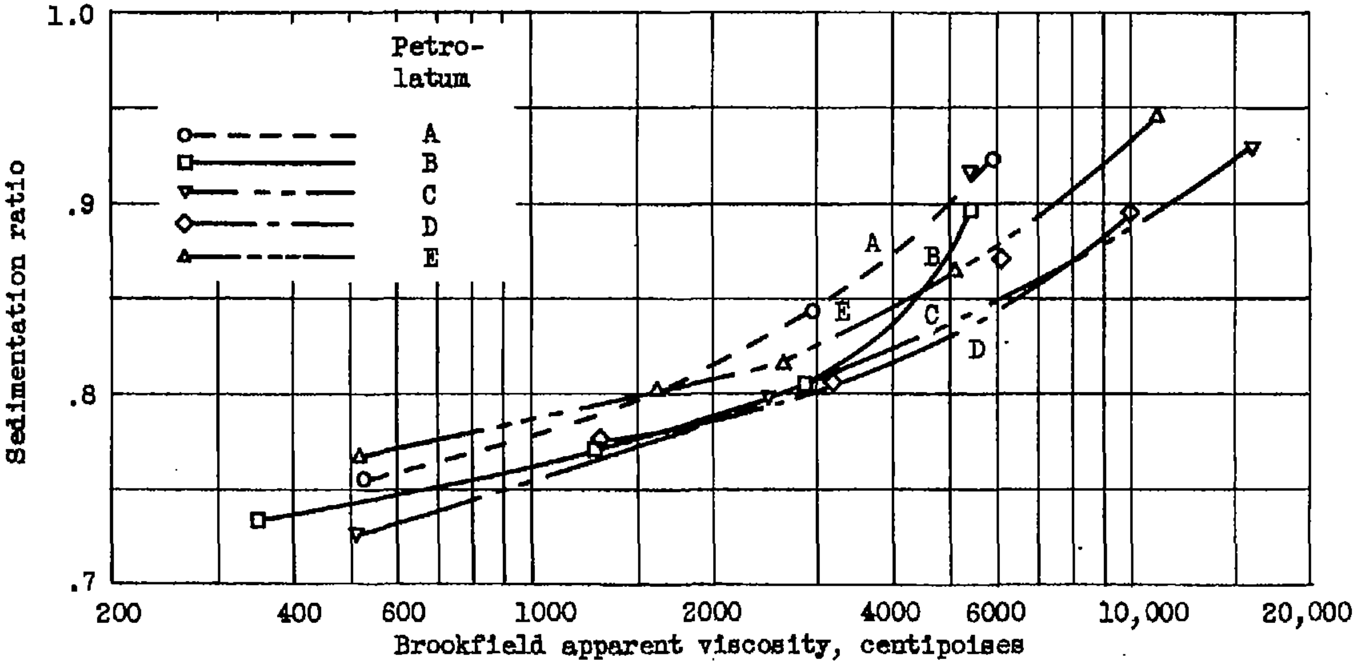
(c) Redispersibility.

Figure 13. - Concluded. Effect of magnesium concentration on physical properties of magnesium slurries stabilized with petrolatum. Hydrocarbon medium composed of 28 percent petrolatum E and 72 percent MIL-F-5624A, grade JP-4 fuel.



(a) Residual viscosity at 75° to 86° F.

Figure 14.- Relation between Brookfield apparent viscosity at 86° F and other measured properties of 50-percent magnesium slurries stabilized with each of five petrolatums. Hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.



(b) Sedimentation ratio at 86° F.

Figure 14. - Continued. Relation between Brookfield apparent viscosity at 86° F and other measured properties of 50-percent magnesium slurries stabilized with each of five petrolatums. Hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.

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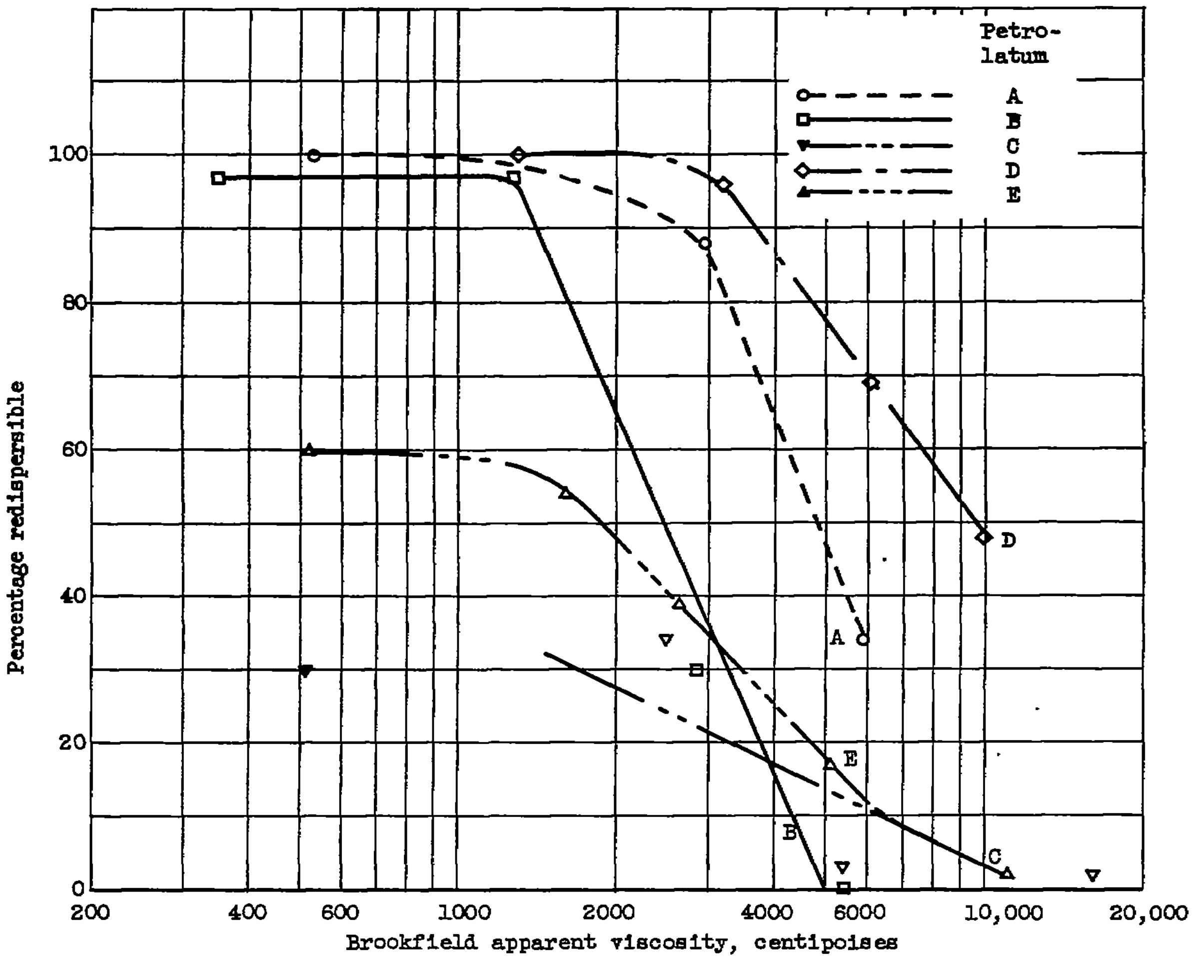

(c) Redispersibility.

Figure 14. - Concluded. Relation between Brookfield apparent viscosity at 86° F and other measured properties of 50-percent magnesium slurries stabilized with each of five petrolatums. Hydrocarbon media composed of petrolatum and MIL-F-5624A, grade JP-4 fuel.

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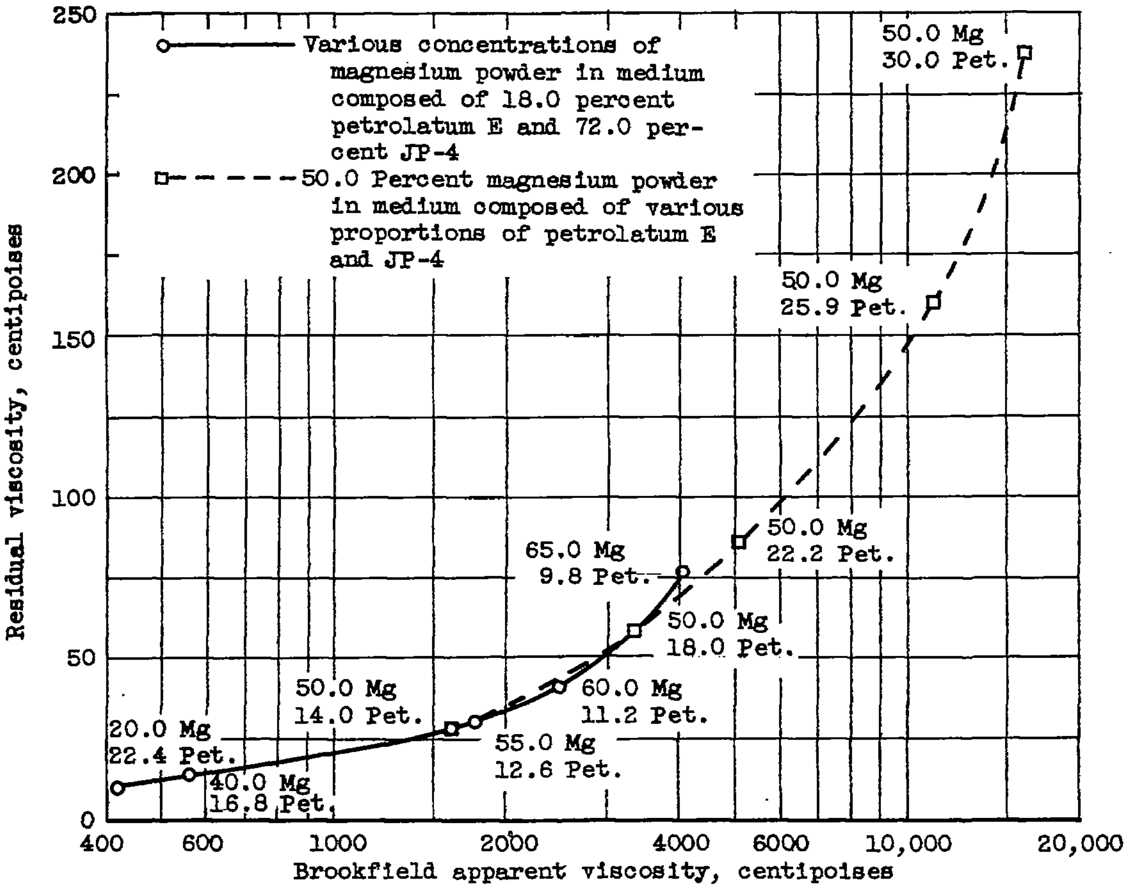
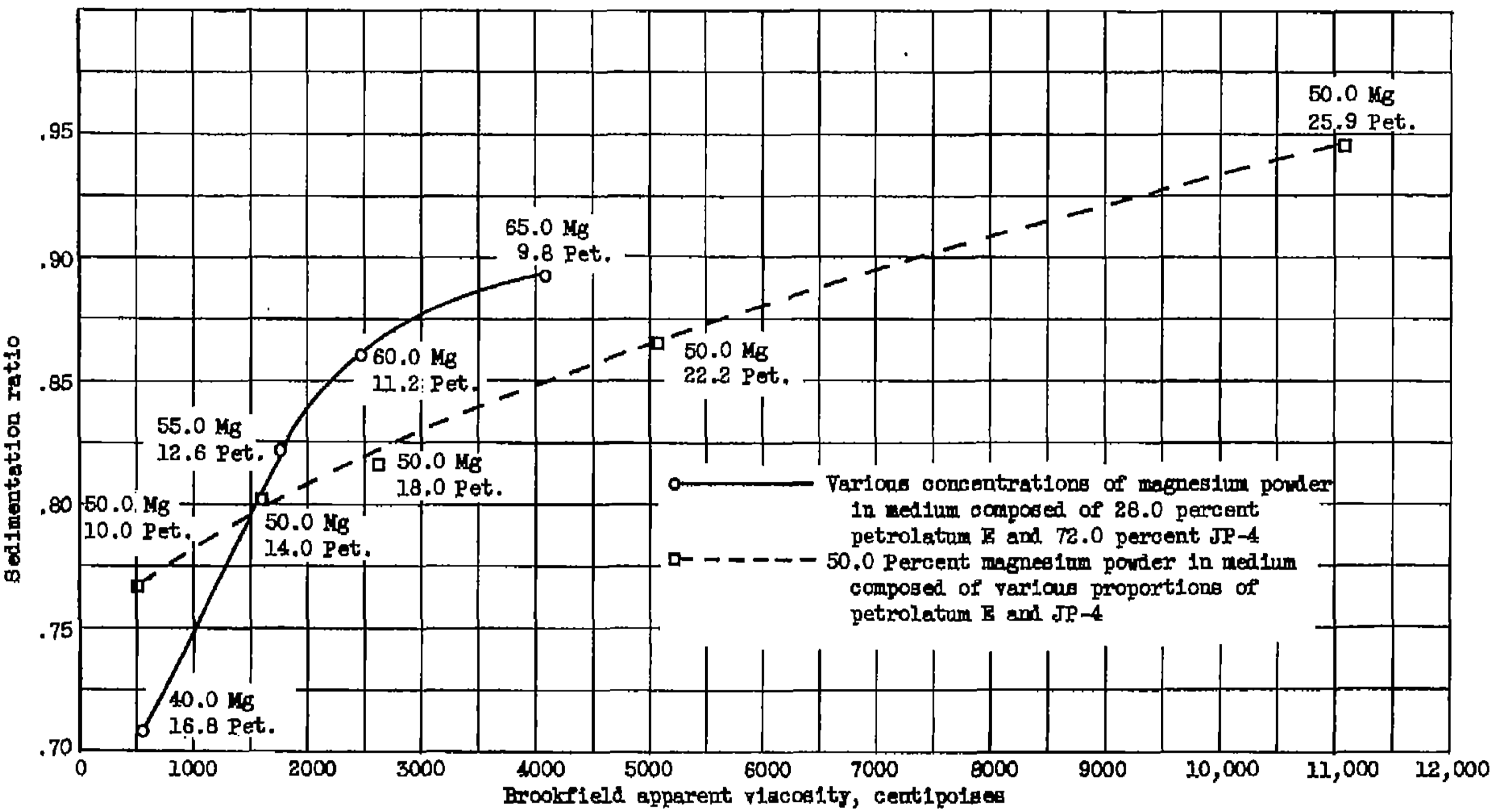


(a) Residual viscosity at 79° to 84° F.

Figure 15. - Comparison of effects of magnesium concentration and petrolatum concentration on relation between Brookfield apparent viscosity at 86° F and other measured properties of slurries. (Numbers for each data point indicate percentages of magnesium and petrolatum in slurry.)

[redacted]



(b) Sedimentation ratio at 86° F.

Figure 15. - Continued. Comparison of effects of magnesium concentration and petrolatum concentration on relation between Brookfield apparent viscosity at 86° F and other measured properties of slurries. (Numbers for each data point indicate percentages of magnesium and petrolatum in slurry.)

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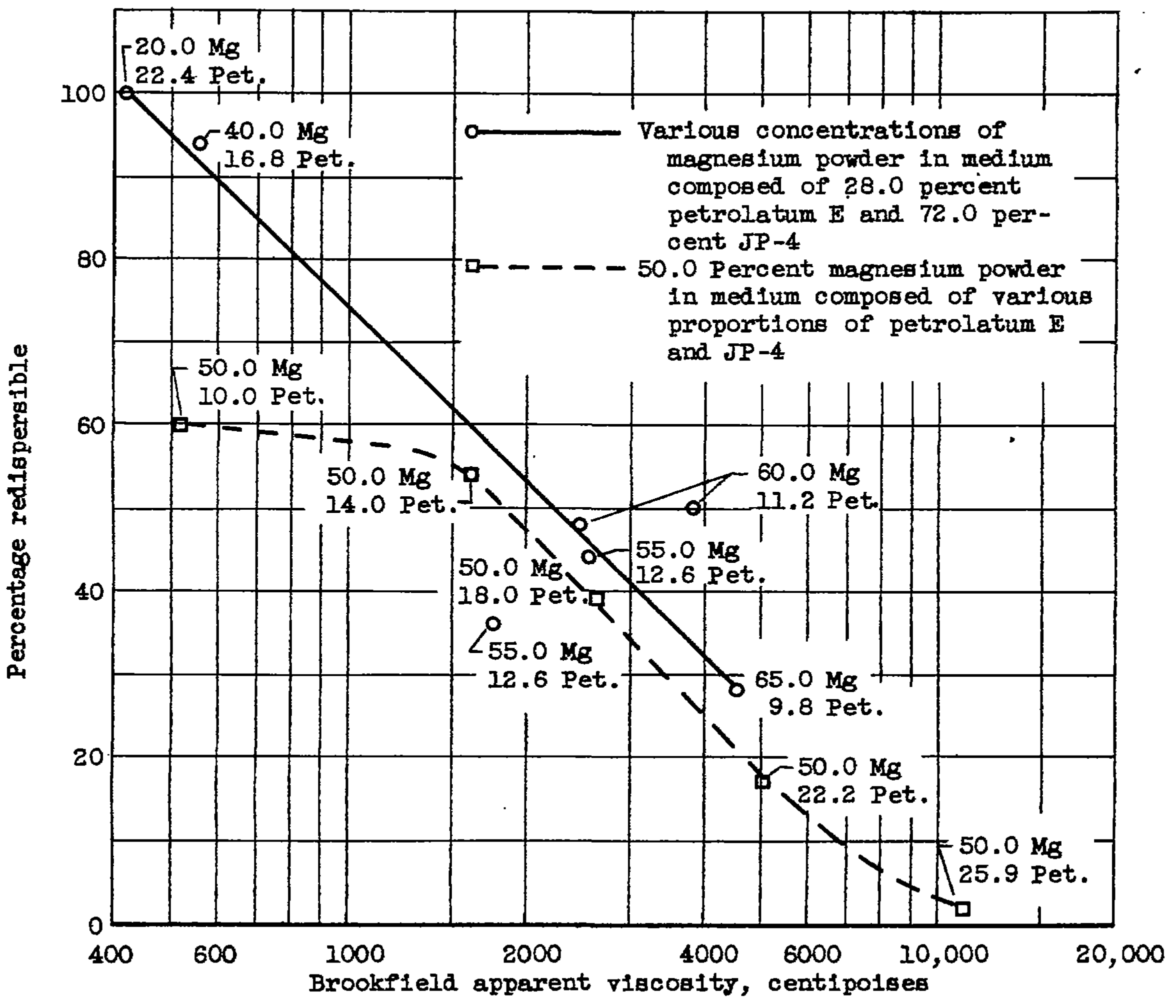

(c) Redispersibility.

Figure 15. - Concluded. Comparison of effects of magnesium concentration and petrolatum concentration on relation between Brookfield apparent viscosity at 86° F and other measured properties of slurries. (Numbers for each data point indicate percentages of magnesium and petrolatum in slurry.)

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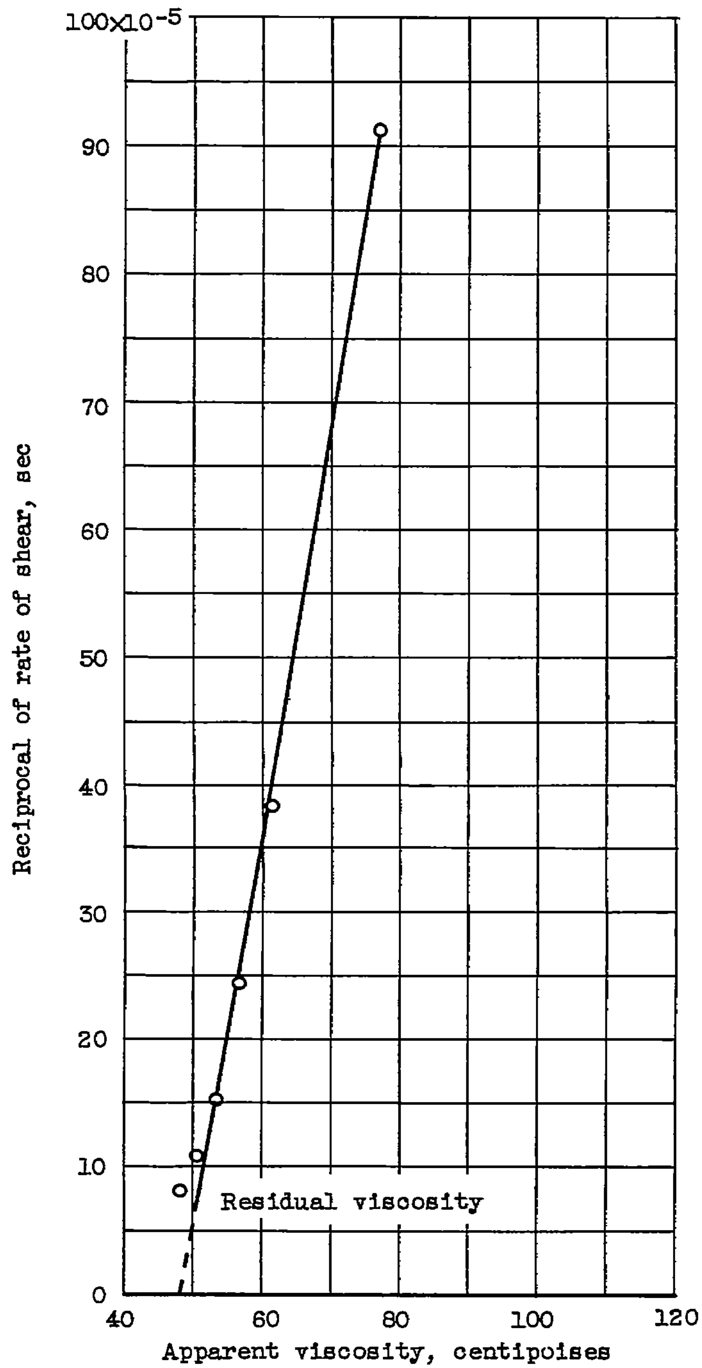

Figure 16. - Method of determination of residual viscosity. Slurry composition: 50 percent magnesium powder; 22.2 percent petrolatum D; 27.8 percent MIL-F-5624A, grade JP-4 fuel.

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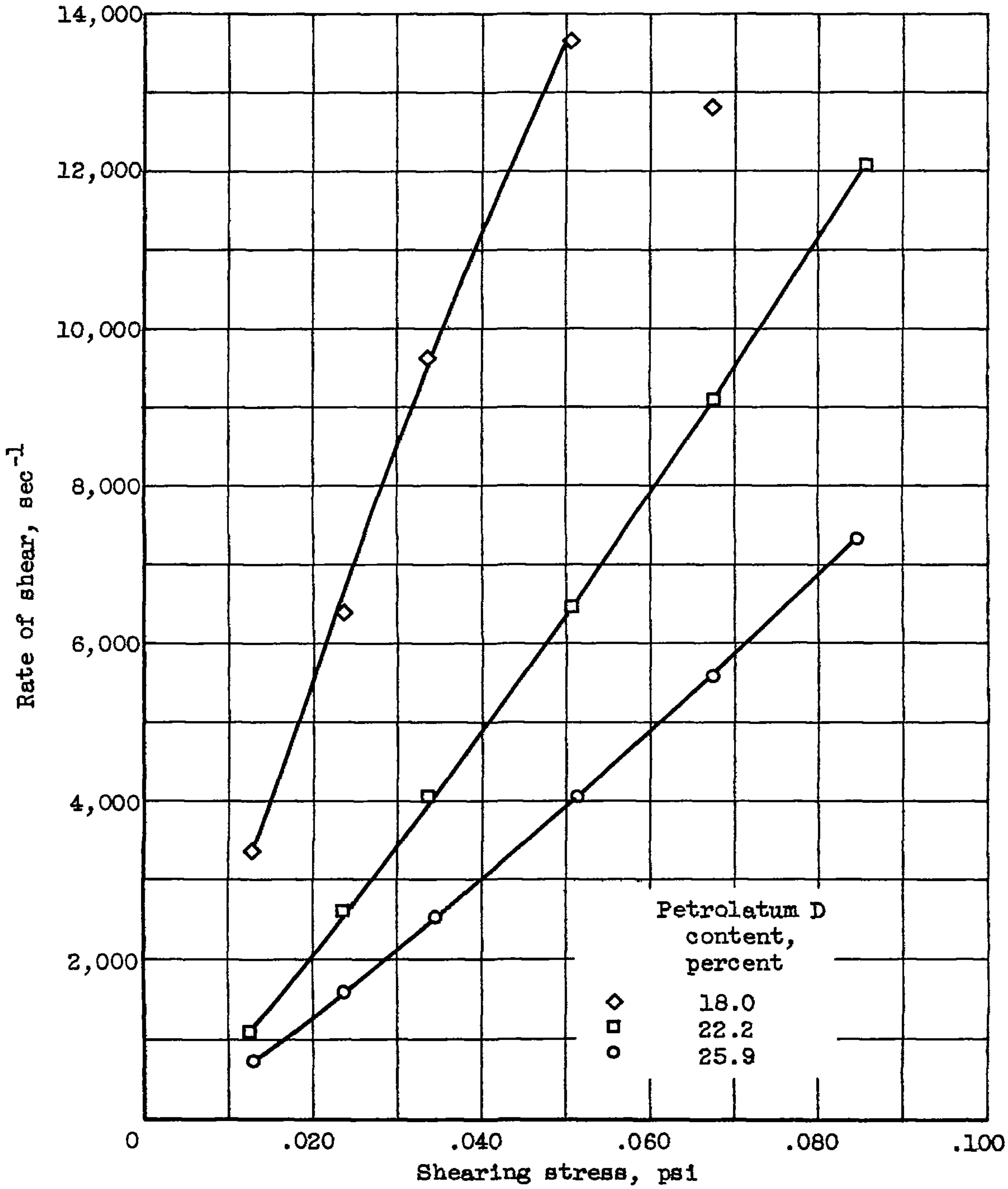

Figure 17. - Rate of shear against shearing stress for 50-percent magnesium slurries stabilized with various concentrations of petrolatum D. Temperature, 82° to 84° F; medium composed of petrolatum D and MIL-F-5624A, grade JP-4 fuel.

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